The Scientific Life

By John R. Baker and J. B. S. Haldane

BIOLOGY IN EVERYDAY LIFE

By John R. Baker

SCIENCE AND THE PLANNED STATE

The Scientific Life

by

JOHN R. BAKER

M.A., D.PHIL., D.SC.

Lecturer in Zoology in the University of Oxford

London

George Allen & Unwin Ltd

FIRST PUBLISHED IN 1942
SECOND IMPRESSION 1944

BOOK
PRODUCTION
WAR ECONOMY
STANDARD

THE BINDING OF THIS BOOK CONFORMS
TO THE BINDING ECONOMY STANDARD

ALL RIGHTS RESERVED

PRINTED IN GREAT BRITAIN
in 11-*Point Imprint Type*
BY BRADFORD & DICKENS
LONDON, W.C.1

Preface

THIS book has been written for those people, scientists and non-scientists alike, who have the welfare of science at heart. In the period of reconstruction after the war the future of science will be decided. Science, long thought impregnable, is now attacked. The attack, subtle and indirect, comes from within. The spirit of free enquiry is threatened today by those who would plan other people's researches and confine investigation to crudely practical ends. If the threat materializes, the spirit of free enquiry will be crushed. That spirit has given mankind its heritage of modern scientific knowledge, and if it be allowed to live it will give new knowledge in ever-increasing measure.

Three wishes accompany this book. I hope that it will help to show research workers and teachers and students of science, and technologists too, that science is threatened. I hope that by its very shortcomings it will stir profounder minds to write on the same subject and thus bring substantial help to the cause of freedom in science.* My third hope is that some parent or science teacher may think fit to put this book into the hands of a thoughtful boy or girl aged fifteen or over, and that as a result that boy or girl will decide to live the scientific life. Before the last wish can be realized, freedom in science must be secured.

I am indebted to Professor A. G. Tansley, F.R.S., and Professor E. S. Goodrich, F.R.S., for kindly reading the manuscript and making many suggestions, most of which I have

* Professor M. Polanyi has now written a profound essay on "The growth of thought in society" (*Economica*, Nov., 1941).

adopted. Professor M. Polanyi and Mr. R. Brown have read parts of the manuscript and given valuable advice. Though not herself a scientist, my wife has made suggestions which have been of real value in most of the chapters. The librarians of the Radcliffe Library have shown never-failing helpfulness.

JOHN R. BAKER

DEPARTMENT OF ZOOLOGY AND COMPARATIVE ANATOMY
UNIVERSITY MUSEUM, OXFORD

Contents

Chapter 1

The Act of Discovery

"Lernen wir träumen, meine Herren, dann finden wir vielleicht die Wahrheit."
KEKULÉ[120]

THE word discovery is used in science with two meanings, though they are not always very distinct. On the one hand a new phenomenon or object may be disclosed, such as the penetrating powers of X-rays or a living specimen of a fish belonging to a group previously thought to have been extinct for millions of years: on the other a new principle or theory may be formulated, as when structural formulae were suggested in organic chemistry or the theory of natural selection put forward as a partial cause of evolution. Discoveries may usually thus be classified as factual or theoretical. In most sciences the factual discoveries are commonly made in the laboratory, but they originate in ways which would be surprising in their diversity to people who are not themselves concerned with scientific research. Ideas for experiments occur unexpectedly to the scientist anywhere and at any time of day or night, often when he is thinking of something else. Chance observations which he makes in his laboratory may suggest quite new lines of investigation. Important factual discoveries probably arise more commonly from such sources as these, than from the rigid following-up of a comprehensive plan of campaign deliberately thought out by the scientist in advance. Theoretical discoveries are seldom produced to order while the sanguine scientist sits conveniently confronted with a blank sheet of paper: they

generally originate, like ideas for new lines of research, when he is far from laboratory or study.

Whenever one is able to look into the mind of a discoverer at the moment of discovery, one sees that the finding out of unknown facts and the origin of great generalizations are not crudely mechanical processes, to be achieved by the efficient sorting of the cards in a card-index or the punctual study of pre-publication abstracts of other people's work. Ideas come in the most unpredictable way, and seldom when they are being sought. One distinguished scientist has told me that his new ideas often come during railway journeys, and several have mentioned the capacity of a hot bath to generate plans for new investigations or for theories to account for what is already known. In the case of Archimedes the startlingly sudden origin of his important hydrostatical concept following the immersion of his own body in his bath has perhaps misled people into assuming that he was thinking of himself as the body submerged, whose weight would lose by submersion as much as was equal to the weight of the bath-water displaced. It seems at least as likely that the bath was acting simply as a generator of ideas.

It need scarcely be said that whatever originates in the train or 'bus or bath or bed or whatever incalculable place it may be, must subsequently be subjected to the most searching analysis in the cold light of the laboratory; but the idea must come first. Let us watch a couple of ideas of the first magnitude coming into the mind of a great German chemist.

So long as people are still interested in the history of science the name of August Kekulé will be honoured, above all for his introduction of structural formulae in organic chemistry and his theory of the constitution of the benzene ring. He was not actually the originator of the concept of valency, but he devised the method of writing down the

formulae of organic compounds which has been universally accepted ever since, on account of its demonstrating so clearly the way in which atoms and groups of atoms are linked together. The mere knowledge that so many carbon atoms, so many hydrogen atoms, etc., enter into a molecule of a substance does not mean very much; but if anyone with chemical knowledge can see, as he can from a structural formula, how they are linked, he can instantly infer many of the properties of the substance.

Kekulé himself has told us how the inspirations came which gave such a great impetus to chemical research. He announced it in his speech in the Berlin Rathaus on 11th March 1890, when the German Chemical Society met there to do him honour on the occasion of the twenty-fifth anniversary of the publication of his theory of the chemical structure of benzene[120]. After the delivery of speeches by notable German chemists and the reading of letters and telegrams in his honour from representatives of chemical societies in various parts of the world, Kekulé made a simple, modest speech in which he told how the two greatest discoveries of his life came to him.

He told how he lived at one time near Clapham Common, and how he often went to Islington to spend the evening with his friend Hugo Müller. One night the two friends had spent the evening together in this way, talking of many things, but mostly of their beloved chemistry. It was summer, and Kekulé went home on the outside of an omnibus. "I sank", he said, "into a reverie. The atoms flitted about before my eyes. I had always seen them in movement, these little beings, but I had never succeeded in interpreting the manner of their movement. That day I saw how two small ones often joined into a little pair; how a larger took hold of two smaller, and a still larger clasped three or even four of the small ones, and how all span round in a whirling round-

dance. I saw how the larger ones formed a row and only at the end of the chain smaller ones trailed along.

"The cry of the conductor, 'Clapham Road', woke me up from my reverie, but I occupied part of the night in putting at least sketches of these dream-products on paper. Thus originated the structure-theory."

It was particularly the formulation of the theory of the benzene-ring that the assembly had met to commemorate, and Kekulé told how this discovery also came to him, a discovery on which one-half of organic chemistry is based and which has proved more fertile than any other discovery in making possible verifiable and true predictions about the properties of substances. Those who have not studied organic chemistry will scarcely be able to comprehend how Kekulé's theory of the structure of benzene revolutionized the subject. In its essence it was a very simple theory: the six carbon atoms of the molecule are arranged in a ring, each linked to the next. The idea of this ring-structure came to Kekulé in another of his reveries.

During his residence at Ghent, he was sitting writing his chemical text-book. "But it did not go well; my spirit was with other things. I turned the chair to the fireplace and sank into a half-sleep. Again the atoms flitted before my eyes." His imaginative eye, sharpened by repeated visions of a similar kind, could by this time distinguish large structures of complicated construction. He had seen rows of atoms linked together, but never yet rings: nor had anyone else. This is how the idea came to him: "Long rows, variously, more closely, united; all in movement, wriggling and turning like snakes. And see, what was that? One of the snakes seized its own tail and the image whirled scornfully before my eyes. As though from a flash of lightning I awoke; this time again I occupied the rest of the night in working out the consequences of the hypothesis."

Kekulé did not tell of these incidents simply for the sake of something to say; he was deliberately advising on how to make discoveries in science. "Let us learn to dream, gentlemen, then perhaps we shall find the truth"; but almost immediately he gave a warning against the publication of the dreams until they had been put to the test of the intelligence when awake.

As the embryologist, Dalcq[28], has insisted, it is wrong to consider sciences as constructions methodically erected according to a thought-out design. "Like all human achievements, they are a fruit of life, and of progress in those directions which happen, at a certain moment, to be favourable." One might add that those who contribute to science are drawn to their work not by any bureaucratic scheming, but by an imperious internal drive: if sufficient drive is there, it will overcome almost all obstacles. Every time a motorist speaks of an amp,* a wireless enthusiast of a microfarad, or a sailor of degaussing, a famous scientist is being commemorated who rose through sheer ability without the aid of wealth at a time when it was much harder to rise than it is today. To anyone with the intense desire to find out that characterizes the research-worker, any other life is tame, whatever attractions it may hold for a different type of person. A recent correspondent in "Nature"[83] has said that young scientists have sometimes concealed their degrees in science in order to get well-paid administrative jobs. He calls this "waste of material", but it may be suggested that this is quite the wrong comment. The men had had a training in science, but it is clear that they were not scientists; and the real waste would have occurred if some one had not realized their deficiencies and had given them posts

* Ampère's father was executed at the time of the French revolution. Still a youth, Ampère supported himself for a time by giving private lessons.

in research laboratories. One discovers or invents because one has an internal urge to do so, unless the environmental conditions make it impossible. Every help should be given to people in all walks of life who have the genuine urge. The help should be encouragement, facilities and a reasonable livelihood. The man who wants the higher pay of an administrative job should be dissuaded from occupying a potential research worker's seat in the laboratory of a scientific institution.

In an amusing advertisement in the "Daily Telegraph" a firm of tool-manufacturers[38] announce that they invent tools because they like inventing tools. This gives the impression of being one of the most truthful advertisements one has ever read: the inventor has an urge which is comparable to that of the discoverer. It is only genuine interest in a subject, and not the hope of reward, that can make a research worker accept willingly the continual rebuffs which he receives in his work. Continually things go wrong: repeatedly he discovers that weeks or months of hard work have been thrown away on a line that will lead nowhere, or some one else discovers the same thing without his knowing it, and it looks as though all the time he has spent on the subject had been wasted. The continual disappointments would cure all but the genuine natural investigator in a very short time of any desire to devote his life to research: he would be unlikely to get so far as experiencing the joy of even a very small discovery. The man who works for reward or fame would never be able to force himself to do all the "useless" reading in subjects not immediately connected with his research that is so often a genuine pleasure to the real scientist. He reads omnivorously when he is not using his hands in his laboratory, and he reads because he is interested. Much that he reads he will never use again: just every now and then a remembrance of something he

read long ago throws light on his immediate problem: he has a new insight into his work. His wider reading is utterly different from that of the writer of a text-book: he need reject nothing because it seems irrelevant, and his wider reading—I am not referring here to his concentrated study of the literature obviously connected with his research—would seem sketchy to anyone who examined him on it. Meanwhile ideas are accumulating, and most of them will lead to nothing; a few, when he is lucky, to discovery.

Nothing but an intense interest in the subject as a whole—in things—could make a man work so long with so many rebuffs and read so much with so little hope of profiting directly. The youthful aspirant to fame, who reads of the honours showered on Pasteur, likes to think of himself as a great medical research worker. He forgets that Pasteur was no aspirant to fame, nor even interested at first in medicine. He was, like all great scientists, intensely absorbed in the study of things. It is useless to desire to become a research worker because one desires fame, and equally useless to do so because one thinks that one can serve the community by scientific research. The man who has the urge to find out serves the community indeed, culturally or materially or both, if given the opportunity; but he does so because he believes in the value of finding out the truth about things. A man with no special talents for music might as well say that he was going to compose a symphony because he owed it to the community, as one without the gifts of the natural investigator undertake scientific research for the same reason. No scientist can tell what he is going to discover: a man might seek something comparable in its beneficence to trichlormethane and end up with a substance so potentially horrible as $\beta\beta$-dichlordiethylsulphide to his credit.

The joy of discovery is a very real incentive to research, despite the rareness of its realization. It is an error to suppose

that the scientist is unemotional, or could succeed if he were. The error has arisen through a misconception. The absolute necessity that a scientist's findings shall not be changed from objective truth in response to emotional urges of any kind does not result in his becoming a particularly unemotional person: whether a discoverer or anyone else is pleased with a discovery has no effect on its validity. "I have been working like a madman at Drosera", wrote Darwin to Sir J. D. Hooker in reference to his study of insectivorous plants, and a few days later, to the geologist, Lyell, "at the present moment I care more about Drosera than the origin of all the species in the world. . . . I am frightened and astounded at my results"[36]. Kropotkin once wrote[84], "There are not many joys in human life equal to the joy of the sudden birth of a generalization. . . . He who has once in his life experienced this joy of scientific creation will never forget it." Kropotkin did not exaggerate, and what he wrote is as applicable to factual as to theoretical discoveries. Let us witness an authentic case of joy in factual discovery.

"All is discovered!" The first shock is such that the young scientist cannot put his eye back to the instrument, but only emits this scarcely articulate cry. He rushes from his laboratory into the corridor. Meeting there a laboratory assistant in physics, he insists on embracing him. The assistant is dragged off to hear an exuberant account of what has transpired[136].

It was Pasteur who spoke. At the age of 25, before he turned to medicine, he made a discovery which, with those of van't Hoff, laid the foundations of the branch of chemistry which is concerned with the actual shapes of the ultimate particles of chemical compounds in the three planes of space.

It was already known that solutions of the salts of tartaric acid (from grape-juice) have a special effect on light. Light reflected from glass, or any other light in which the waves

vibrate in one plane instead of (as in sunlight) in all planes at random, is affected by a solution of one of these salts. The light emerges from the solution with the waves still all vibrating in one plane, but the plane is a different one: the plane of polarization has been rotated to the right. Pasteur's discovery was this[72]. He found that when he evaporated a solution of a salt of an acid very closely allied to tartaric acid, two sorts of crystals were produced, differing only in the positions of certain of their surfaces, so that one kind might be called right-handed and the other left. One kind of crystal was a familiar one, the other quite new. Pasteur was able, with the aid of the microscope, to separate the right-handed from the left-handed crystals, though the differences were small and the possibility of the existence of such differences not previously envisaged. He dissolved each kind of crystal separately and passed a beam of polarized light through each solution.

What he saw was the cause of Pasteur's excitement. One solution changed the plane of vibration in the usual way, to the right: the other, made from the new kind of crystals, changed it to the opposite direction, to the left. Thus the symmetry of the crystals was correlated with the optical behaviour of their solutions, and an insight was given into the structure in the three planes of space of the ultimate particles of which chemical compounds are formed.

The excitement and joy of making a discovery is known to every research worker, though in Britain the expression of the emotion is more reserved, so that when our colleague discovers something and we play the part of the laboratory assistant in physics in the corridor, we avoid the necessity of being kissed. The emotion is there whether the discovery is big or small, whatever the nationality of the discoverer may be. Let us watch a very great British scientist making a very small discovery.

Alfred Russel Wallace, co-founder with Charles Darwin of the theory of evolution by natural selection, catches a new species of butterfly in the Moluccas. It is a particularly brilliant species of the genus Ornithoptera. "None but a naturalist", wrote Wallace[140], "can understand the intense excitement I experienced when I at length captured it. On taking it out of my net and opening the glorious wings, my heart began to beat violently, the blood rushed to my head, and I felt much more like fainting than I have done when in apprehension of immediate death. I had a headache the rest of the day, so great was the excitement produced by what will appear to most people a very inadequate cause."

The joy of a discovery, big or small, is shared by a scientist's colleagues. The enthusiasm is infectious. Pasteur's crystallographic discovery illustrates the fact very pleasantly. He asked the old French chemist, Biot, for permission to demonstrate his results to him. Biot agreed, insisting that his own materials should be used and the test made in his own laboratory. The solution was made and allowed to evaporate for a couple of days. When sufficient crystals had appeared, Biot called Pasteur once more to his laboratory and in the former's presence the young scientist separated the right-handed crystals one by one from the left-handed. Biot dissolved them and decided first to examine the solution which should, according to Pasteur, rotate polarized light to the left. This was the solution of the new kind of crystal, with hitherto unexpected optical properties. Biot called Pasteur once more to his laboratory and proceeded to observe the effect on polarized light. He knew at once that a great discovery had been made. He seized Pasteur's arm and exclaimed, "My dear child, I have loved science so much in my life that that makes my heart throb."[136]

It was the sudden birth of a generalization—a theoretical discovery—that Kropotkin held to be so particularly joyful.

Pasteur's discovery was factual, but not less satisfying for that. Kekulé's reveries resulted in theoretical discoveries. We may attend with advantage at the birth of another theoretical discovery, this time in biology, as important for science and as satisfying to its maker as Kekulé's.

Wallace himself regarded his work in describing and working out the distribution of the insects which he collected in the East Indies as incompletely satisfying or "comparatively profitless", as he expressed it[92]. We should realize that he was comparing the "profit" with that of his great work on evolution by natural selection. The circumstances under which the great generalization was born in Wallace's mind are known. To Charles Darwin—originator of the phrase "natural selection"—the same great generalization came very slowly: upon Wallace, to use his own expression, it "flashed". One is reminded of Kekulé's comparison with a flash of lightning, when he conceived the structure of the benzene ring. Wallace and Darwin discovered independently the theory of a cause of evolution which is still, in an improved form, the most widely held today and has been a great stimulus to research.

Wallace was in his bungalow in the little island of Ternate in the Moluccas, his headquarters for the study of the fauna of the East Indies. Here, amid all the treasures of natural history that he had collected, the great naturalist was taking an enforced holiday as a result of repeated attacks of malarial fever. It was during an actual attack of fever that the idea came to him. His mind was reflecting on Malthus's "Principles of Population", and he brought his remembrance of this book, which he had read twelve years before, into connexion with the vast stores of knowledge that he had gained of the lives of wild animals in their native haunts in the East Indies. It was a supreme example of the value of wide reading to research workers. The principle of the survival

of the fittest "suddenly flashed" upon him. "Then at once", he wrote, "I seemed to see the whole effect of this", and he waited impatiently for his fit of fever to leave him, so that he could write down a sketch of his theory. That same evening he did so, and during the next two evenings he wrote out a fuller account to send to Darwin.

The scientist would be a self-centred person if he cared nothing for the good opinion of his colleagues. It is not fame that he wants, for that would mean that he respected a value set upon his work by those who could not be in a position to assess it truly. The good opinion of colleagues is desired by nearly every research worker, and when it is gained—and it can only be gained by the revelation of demonstrable truth—there is a satisfaction as great as and perhaps more lasting than the initial joy in discovery, a satisfaction all the more real because others can take genuine unselfish pleasure, like Biot, in the discovery. Ray Lankester expressed these feelings very directly when he gave an account of the first known fresh-water jelly-fish.

One Thursday in the summer of 1880 the Secretary of the Botanical Society of London noticed some strange organisms floating in a warm-water tank, in the house in Regent's Park devoted to the cultivation of the magnificent water-lily, Victoria regia. By the following Monday he had placed a number of specimens at Lankester's disposal. The organisms were jelly-fish. Never previously had a jelly-fish (Medusa) been known to inhabit fresh water: the kinds of animals popularly so called were thought by the best scientific opinion of the time to be exclusively marine. Lankester wasted no time; nor did Allman[4], another distinguished zoologist, to whom the Secretary also gave some specimens. On the Thursday morning, just one week from the time the organism was first seen, a description of it by Lankester was already in print[85], and on the same afternoon Allman was

describing it at the Linnean Society. (By the inflexible law of priority, Lankester's name of Craspedacusta was accepted for the animal in preference to Allman's Limnocodium, though Lankester, with a somewhat Irish gesture, tried simultaneously to change his name into a philologically more exact form and to withdraw it altogether out of respect for Allman.) A week later quite a long paper on the physiology of the new animal was already published by the celebrated biologist whose memory is kept fresh in Oxford by the Romanes lectures, still delivered annually on scientific or literary topics[116]. On the same day Lankester wrote[86]: "I confess to having worked at that Medusa day and night when I first obtained it, with the object of having the pleasure and honour of being the first to expound its structure to my brother naturalists."

Lankester referred to the pleasure and honour of his work; Darwin in his autobiography put love of science first in the list of the mental qualities which gave him success in research[36]. It may be left to a philosopher to describe more particularly the value of science to the scientist. The pleasure of science, as Alexander[3] says, "is sometimes felt passionately, most often it is a calm delight in contemplating the harmonies of knowledge. It may be attended by subsidiary excitements in the work of investigation, some of which are pleasurable in so far as the labour tends to success; others involve pain or suspense. The release from such tension, when disappointment and frustration are replaced by discovery, adds a glow to the exercise of the search. . . . Truth is the satisfaction of disinterested curiosity."

Chapter 2

Scientists as People

One day I was sitting at a window with a friend, when an eminent scientist pedalled sedately by on his bicycle. My friend was unacquainted with the personalities of science. I remarked that we had just seen a particularly distinguished Fellow of the Royal Society. "What?" he exclaimed, "a Fellow of the Royal Society? He looks more like the man who comes to mend one's umbrella." Never having been visited by anyone anxious to perform this particular service, I could not form an exact idea of how the scientist appeared to my friend; but it was clear that the impression was unfavourable. The public has certain ideas of what a scientist should look like and how he should behave. As Waddington[139] has recently remarked, the popular idea of a scientist is of someone removed from ordinary human realities. On reflection, it seems strange that there should be such a thing as a popular idea on the subject at all, for the great majority of human beings have not only never themselves made the smallest contribution to knowledge in the scientific sense, but have never known personally anyone who has. Nevertheless, there is some truth in the idea described as popular.

In ordinary life loyalty and steadfastness in opinion are admired. A scientific friend of mine was described by another scientist as "loyal to his professor". The accusation of being loyal to his professor's scientific views was intended and received as a deliberate insult, for scientists acknowledge no loyalty to the opinions of persons, but only to the truth as it appears to themselves. They give honour to one another

for change of opinion. In 1855 T. H. Huxley strongly attacked what he called the "fallacious doctrine"[78] of evolution. Five years later his opinion had completely changed, and he delivered his famous and shattering attack on the Bishop of Oxford, who sought to ridicule Darwin's views. The episode occurred in a room in the University Museum at Oxford, and there is now a plaque outside the door to commemorate it. The Bishop had taunted Huxley on his belief in his own (Huxley's) descent from an ape. Huxley's reply is well known. "I asserted, and I repeat," he said, "that a man has no reason to be ashamed of having an ape for his grandfather. If there were an ancestor whom I should feel shame in recalling, it would be a *man*, a man of restless and versatile intellect, who not content with an equivocal success in his own sphere of activity, plunges into scientific questions with which he has no real acquaintance, only to obscure them by an aimless rhetoric, and distract the attention of his hearers from the real point at issue by eloquent digressions, and skilled appeal to religious prejudice"[36]. The doctrine of evolution no longer appeared fallacious to Huxley, and he was respected for changing his views.

The eminent geneticist, Bateson, opposed the chromosome theory of heredity almost throughout his working life. Not long before he died he visited America, saw for himself the chromosome preparations that had convinced others long before, and changed his mind. "I am heartily glad I came", he wrote from America[14]. "I was drifting into an untenable position which would soon have become ridiculous." Bateson was respected for his change of opinion.

The popular idea that scientists are often absent-minded is not wrong: it only means that they are present-minded on something other than the trivialities of ordinary life. From a child onwards van't Hoff was fond of daydreaming[47]. When he was twenty-two he formulated a theory which became

one of the foundations of stereochemistry. He could not have done that if his mind had been much concentrated on the little matters of his immediate surroundings. Kekulé's dreams have already been mentioned; the 'bus conductor probably found him absent-minded when the idea of structural formulae was forming in his brain. Bateson has related how "having supposed I had a ticket for "The Pillars of Society" I found myself at a musical extravaganza by some mistake". The very next night he went to hear "Siegfried", but "unfortunately I was half an hour late through mistaking the time". His pencil, notebook, knife, forceps, scissors, pipe and spectacles were perpetually mislaid. He would go to London in old "garden" flannels, darned across the knee, but wear a brand-new "town" suit in the garden and kneel on the gritty path to look at his plants[14]. This kind of behaviour is commoner among research workers than in most walks of life. We are told[80] that at an interview with a young scientist Einstein was dressed in a morning coat and "striped trousers with one important button missing".

If the scientist tends to be rather peculiar in an inoffensive way, then the nature of his work often gives him more than an ordinary share of certain virtues which are also common outside science. A sort of kindliness is engendered by continued observance of cause and effect, and savage hates are foreign to the scientific mind. A spread of scientific culture would lessen racial animosity and thoughtless dislikes of many kinds. It is strange to the mind of a scientist that anyone should want to persecute a person because he is a Jew, a communist or a kulak. The scientist's attitude is one of interest in the ethnological, psychological or sociological circumstances which produce those three categories of persons. (Incidentally, the debt of science to Jewish research workers is so great that the thought of the persecution of their race is particularly abhorrent to scientists.)

The great mountaineer, Whymper, was not a scientist. He devoted some pages of a perfectly serious book[144] to the cretins and sufferers from goitre in the valleys of the Alps. He was horrified by these people in a way which would be impossible to a scientist, who would regard the diseases impersonally and look for the cause. Whymper allowed his horror to grow to hatred, and wished to think that the sufferers or their parents were themselves to blame. He wanted those suffering from goitre to be conscribed into monstrous armies, to be commanded by idiot cretins. He wanted illegitimate cretins to be subject to "special disabilities", as though the frightful disability of cretinism were not a sufficient punishment for innocent persons. That people should think in this way appals the scientist. Of a great geneticist, for instance, it was written, "There was no place for punishment in his philosophy"[14]. Research has exhibited the folly of the mountaineer. Lack of iodine in the drinking water, not wickedness, is the cause of the diseases. One ounce of iodine in seven and a half million gallons produces a drinking-water which will ward off goitre[146], while feeding with thyroid gland or its extract has a markedly beneficial effect on cretinism.

Hand in hand with the lack of hate towards others there sometimes goes an almost childish unwillingness to believe in the guile or hatred of others. An incident in the life of Archimedes illustrates this kind of unworldliness. When Syracuse was besieged by the Romans in 212 B.C., Archimedes put his great inventive power at the disposal of the defenders. It was in vain, for the city was taken by surprise. Exactly what happened is uncertain[63], but it would appear that Archimedes was absorbed in the solution of a geometrical problem and did not notice that the Roman soldiers had arrived. When one of them approached to take him prisoner, he asked for time to solve his problem. The soldier answered

by drawing his sword. A moment later the great mathematician and scientist was dead.

Modesty is another virtue particularly common in scientists. The work itself and the appreciation of colleagues are the only rewards desired. Collip, who played an important part in the research which gave the world insulin, wrote these words: "The part which I was able to contribute subsequently to the work of the team was only that which any well-trained biochemist could be expected to contribute, and was indeed very trivial by comparison with Banting's contribution"[22]. The modesty of these words is impressive, and a good example of a trait which is probably commoner in the scientific than in most professions. Another good example of modesty is furnished by Ernst Abbe, the great German computer of microscope lenses. When he introduced apochromatic lenses and thus revolutionized critical microscopy, his paper was so written as to "avoid even hinting at the almost gigantic work of calculation" which underlay their design. As one who knew him well remarks[115], "an attentive reader will see that Abbe was totally innocent of any tendency towards self-praise." Among scientists conceit and arrogance are rare.

There is a simplicity about most scientists, especially great ones, which is attractive. The discoverer does not wish to pose as an encyclopaedic slot-machine: indeed, those whose knowledge is the greatest are seldom the most successful in research. I shall always remember the wise words which were spoken to me many years ago when I was about to address the Royal Society. The Secretary took me aside just as we were about to enter the lecture-room. "Now remember," he said, "you are going to speak to eminent scientists; so you must speak very simply." Had they devoted their lives to the cultivation of omniscience, they could not have become eminent in scientific research.

An incident in the life of Pasteur shows conclusively that great knowledge is not necessarily required for success in research. The great scientist was persuaded, despite his ignorance of the subject, to study the diseases which were becoming a menace to the French silkworm industry. On arrival at the region where the epidemics were at their worst, he met the French naturalist, Fabre, and asked him for information about the natural history of the silkworm moth. Fabre has recorded the conversation which ensued[46]. The great scientist was not aware that the cocoon contained a transformed larva called a chrysalis. Six years from then the diseases were conquered and the silk industry of France saved, thanks to Pasteur's investigations; and an important step forward had been taken towards the understanding of the relation between germs and disease in general. At the start he had not known a fact familiar to most children. His ignorance made a deep impression on Fabre, who knew and admired Pasteur's work in crystallography and bacteriology. Pasteur's "magnificent assurance impressed me", he wrote; "I was astounded; more, I was filled with wonder." Subsequently he deliberately made it a rule to adopt what he called the "method of ignorance" in his own entomological researches.

Great scientists are often simple in another way: they prefer simple apparatus. In these days there is sometimes a sort of competition between institutions in the size and cost of their more spectacular instruments. The cyclotron is a very large and very expensive apparatus used to accelerate electrified particles in experiments on the bombardment of atoms. Each institution anxiously announces the tonnage of its own instrument, like a shipping firm intent on impressing the public by the magnificence of its property. The greatest discoverers have acted differently. Von Baeyer, the brilliant German synthetic chemist known above all for his researches

on indigo, always worked with the simplest possible apparatus, mainly test-tubes, glass rods, small flasks and beakers. He used no large piece of apparatus and no elaborate mechanical device. Perkin, the great British chemist who revealed the chemical constitution of camphor and of various natural dyestuffs and alkaloids, also used the simplest equipment[64]. Wollaston, discoverer of two elements and of the dark lines in the solar spectrum and inventor of the reflecting goniometer, carried simplicity still further than Baeyer and Perkin. A foreigner once called and asked to see the great scientist's laboratory. It was not necessary to move from the room to do so. Wollaston instructed his butler to bring his laboratory, and the order was obeyed—on a tea-tray[55].

Scientists are more comparable to musicians and artists than to business men and politicians, and it frequently happens that they are themselves musical or artistic. Galileo, for instance, was a skilful amateur musician, and Perkin was equal to a professional in this respect[64]. Anyone who has witnessed a performance of "Prince Igor" and been thrilled by the amazing vitality of the musical accompaniment to the Polovtsy dances may find it difficult to reconcile what he has heard with the sober fact that the composer, Borodin, was assistant professor of chemistry at St. Petersburg Academy of Medicine and later lecturer in the same subject at the school of medicine for women which he himself had helped to found. Rimsky-Korsakoff has told how Borodin would suddenly leave a conversation on music in his house to dash along to the adjoining laboratory, making the connecting corridor ring with some extraordinary passage of ninths or seconds. Having assured himself that everything was well in the chemical sphere, he would return to the house for more talk and music[83a].

Scorn has recently been poured on the pursuit of pure science as an "elegant pastime". Some of the greatest scien-

tists have openly practised elegant pastimes. Perkin was an expert on Malmaison carnations[64]. Many scientists adopt a science other than their own for spare-time interest. Armstrong, the chemist, was interested in the geological basis of scenery[8]: the discoverer of the penetrating powers of X-rays was a student of Alpine flora during his holidays[52]. Those who scorn "elegant pastimes" are apt to think scientists childish, because neither children's play nor the pursuit of knowledge has immediate application to material affairs. Scientists will not be horrified at being regarded as childish; they regard the "childlike simplicity and unworldliness"[51a] of Faraday as a virtue, not a vice. The enthusiasm of a child remains as the enthusiasm of an old scientist, while others flatter themselves on being grown-up. The interest of a child in his environment remains as a scientist's interest in nature: he does not undergo a metamorphosis into a different kind of creature, as though he were a chrysalis turning into a butterfly. The good scientist does not pretend that his interest in things is of a different kind from that which he experienced when a child. He has the satisfaction of knowing that it was the assiduous cultivation of such interests by generations of scientists that gave the world its cultural and material treasures of knowledge. The actual interests of childhood often persist in both science and technology. A boy called Sidney Camm was enthusiastically interested in model aeroplanes: as a man, the designer of the Hurricane fighter, he saved his country in the Battle o' Britain[41]. Hogben has announced[71] that when he became a man, he put away childish things; but this is unusual in discoverers. An adult scientist has been known to spend a quarter of an hour playing with the "up" and "down" buttons of an electric lift, "thoroughly enjoying himself, laughing delightedly like a youngster at play"[145]. This will scandalize those who think that a scientist should be quite

a different sort of human being from the child from whom he developed. It is perhaps because the scientist on the lift retains some spirit of childishness that he is such a very great man. It was Albert Einstein, at the height of his intellectual powers.

The scientist likes using his hands, as many children do; he could not succeed in his work if he did not. He does not claim that his childish enjoyment disappeared at maturity and was replaced by an entirely different phenomenon. He knows that his childish manipulations developed steadily into those which serve him so well in the laboratory. He is immune to the sneers of people who say that he has become a scientist because he wants a "legitimate excuse to engage in enjoyable tinkering"[26]. People sometimes jealously express their disapproval of scientists being allowed to do what they enjoy doing in their laboratories, while so many have uncongenial occupations. Those who profess these sentiments do not know what they are talking about. The majority of people, if they could glimpse the future, would view with nothing less than horror a condemnation to a life-time of scientific research. They would shrink from what they would regard as the unutterable boredom of it, and from the repeated disappointments which are a necessary concomitant. Ambitious people would do everything in their power to avoid a life in which success is generally recognized only by a small circle of fellow-workers.

The true scientist does not want public applause. He is a curious mixture of extrovert and introvert. In so far as he necessarily pours out his libido on objects external to himself, he is an extrovert; and certainly he does not turn his mind in upon his own soul in the manner of a character in a Russian novel. A certain withdrawal from the superficialities of everyday life is, however, almost necessary if the internal mental life is to be given a chance to produce results. He

does not find satisfaction in the direction of others: he wants quietude to think. In these respects he is an introvert.

Some degree of withdrawal from social life is recorded again and again in the biographies of great scientists. Galen, one of the early exponents of true scientific method, expressed several times in his writings his scorn for people who spend their time going about saluting their friends[129]. Wollaston, again, to take a random example characteristic of many, is described as a silent, austere man, living only for his work, seldom taking part in social life and then only at the Royal Society or Royal Society Club[130]. Of Graham, the originator of the scientific study of colloids, it was written that he was "Too retired, too quiet. . . . Very intimate friends he had few"[119]. Darwin felt confused in a large gathering: he was oppressed by the numbers of people at Royal Society soirées[36]. Nine days before his marriage he was wondering, in a letter to his future wife, why he "should so entirely rest my notions of happiness on quietness and a good deal of solitude"[87]. He almost seemed to welcome ill-health, which "has saved me from the distractions of society and amusement". "We have given up all parties," he wrote, "for they agree with neither of us." Faraday "took little part in social movements, and went little into society"[51a]. Instances like these could be multiplied. Mendel was "extremely reserved" and had very few intimates[79a]. He lived in a monastery, grew peas in the strip of garden beneath its little clock-tower, addressed the Brünn Society for the Study of Natural Science, and made discoveries in genetics which dwarf everything else that has ever been done in that science before or since, a science which is not only of the utmost academic interest, but is already, despite its youth, playing a large part in practical affairs.

It has been written of Dirac, the eminent physicist whose book on quantum mechanics has been compared in impor-

tance with Newton's "Principia", that "His loneliness and shyness were famous. . . . Only a few men could penetrate his solitude"[80]. Similarly Einstein "remains lonely, loving solitude, isolation and conditions which secure undisturbed work". He suggested jobs as lighthouse-keepers for refugee scientists, so that they might have the isolation necessary for scientific work. In the present century, as in former times, some of the greatest scientific work continues to be done by those who are by nature solitary. "I am a horse for single harness", wrote Einstein, "not cut out for tandem or team-work"[80].

One of the most extreme instances of unsociability that is to be found in human history is provided by a scientist. This man was known to flee from a company of strangers uttering a queer cry like a frightened animal[81]. He took his solitary walks after sundown, so as not to be observed, and made unusual sounds while so employed. He was seriously described by an acquaintance as more silent than the Trappist monks. He had his library four miles from his home, so as to avoid unnecessary meetings with people coming to consult his books[7]. (Incidentally he allowed his friends free use of his library, but would not permit himself to take out a book without leaving a receipt[76a]). He once wrote that to increase his acquaintance was "the thing which I chiefly study to decline"[26]. With his unsociability went a childlike unworldliness. When a plea was made to him for the relief of one of his librarians during illness, he had no idea how much money he should give, and offered £10,000. When dying, as when living, he wished to be alone. His wish, expressed as a positive order to one who would stay with him, was granted[130].

The reader may say that this was not a scientist, but a madman. He happens to have been one of the greatest scientists the world has ever known. Henry Cavendish

(1731–1810) was the discoverer of specific heat, one of the earliest investigators of latent heat, the first serious student of the properties of hydrogen and carbon dioxide, discoverer of the chemical composition of water, discoverer of nitric acid, discoverer (before Coulomb) of the inverse-square law in static electricity, and the first to get an approximation to the density of the earth by experiment.

Our modern scientific moralists are fond of telling us of the wickedness of academic scientists, who are often rather retiring people and somewhat inclined to shut themselves up in their laboratories away from the outside world. These moralists speak of the "integrated" life, the full life, the life which they think everyone ought to lead, scientist and non-scientist alike. This attitude is part of their general desire for uniformity and hatred of individualism. It never occurs to those who profess the integrated life to reflect on the history of science and notice what a large share in scientific discovery has been played by people who could lay no claim to integration. Great discoverers rarely have the inclination, or indeed the ability, to practise the "integrated" life, excellent as this ideal may be for those who are not absorbed in scientific investigation.

There are those who think that quietude, seclusion and freedom may be allowed to geniuses, but not to lesser minds. It will be recollected that Pavlov, the celebrated Russian physiologist, was allowed to avoid planned science and to exist as a sort of museum-piece of freedom in a totalitarian state. Before it is decided to adopt such a practice in our own country, it would be well to consider the nature of scientific genius.

Only a superficial person or one suffering from feelings of inferiority will deny that persons of exceptional talent do exist. A thoughtless person, having once grasped the principle of the structure of the benzene ring, may deceive

himself into imagining it so simple that anyone might have thought of it. This would reveal historical ignorance. Let anyone who is inclined to think such thoughts engage himself in the heavy task of forgetting everything he knows about chemistry except what was known when Kekulé put forward his theory. Let him study in detail the conflicting evidence available at that time as to the structure of the benzene molecule. Let him remember also that at the present moment there must be a multitude of concepts of equal importance and simplicity in science simply calling out for recognition. Most scientists cannot see them and prefer to plod along, checking here, reinvestigating there, following blindly the safe old tram-lines.

Geniuses, then, exist; but their recognition presents a difficulty: the less one knows about a subject, the easier it is to recognize the geniuses. With a little knowledge, one rattles off their names with confidence. In chemistry, for instance, omitting people alive today, one may unhesitatingly enumerate Priestley, Lavoisier, Dalton, Avogadro, Graham, Kekulé, Mendeléeff, van't Hoff, Arrhenius. If one knows something about a subject—let us say biology—the difficulty is more considerable. One begins with Darwin, certainly, and Mendel; but then trouble begins. The trouble is not caused by lack of great men, but by the profusion of them. One realizes that at certain times certain possibilities of discovery were "in the air"; that if one person had not made the discoveries, another, nearly as good, would probably have done so. Here is an obvious distinction from a kind of genius that occurs outside science. If Mozart had not composed that immortal work of genius, the overture to "Le Nozze di Figaro," no one else would ever have done so; but if Kekulé had not lived, structural formulae and the benzene ring would not have remained for ever hidden: someone else would eventually have dreamed the same dreams.

The genius in science is not a man apart. If intelligence could be measured statistically in such a way as to include the extremes, it is scarcely to be doubted that the results would be displayed by an ordinary variability polygon, with the great majority of people possessing ordinary ability of various degrees and fewer and fewer in each grade as the extremes of genius and idiocy were approached. Those who are less than geniuses are very important indeed in scientific research: they make an enormous contribution to discovery. If Bach, Mozart, Beethoven and Wagner had never lived, music would be immeasurably poorer: there have never been four chemists whose work was so essential for chemistry as theirs for music.

Those who are less than geniuses in science are comparable with geniuses in their mental make-up in matters not obviously connected with science. There is the same necessity for a reasonable degree of quietude and separation from the stress of affairs, so that the mind may be open to receive the original ideas which come so rarely and are the basis of discovery. In Great Britain science occupies only one or two persons in ten thousand. Many scientists are wholly engaged in industry and teaching. Only a few hundreds altogether in the whole country are research workers in pure science. Does the community want to dry up discovery at its source? If not, it can afford to grant some degree of quietude to its investigators.

It may seem paradoxical, but the research worker sometimes can and does obtain the necessary mental quietude while bombs are heard to fall outside; but he cannot obtain it if he throws himself heart and soul into the conflict of politics, where all his values, above all his regard for truth and open-mindedness, are out of place, where injustice is as a matter of course condoned as expediency, and where friendship for those with whom one disagrees may be mis-

construed as disloyalty. All this makes an atmosphere which is uncongenial to the research scientist, and it would be beside the point to tell him that he "ought" to put up with what is uncongenial. The community should ask itself whether it wants the scientist to discover or not: if so, let it give him the tools, and he will do the job. His wants are small: he should have a reasonable livelihood and a reasonable share of quietude, and he will make cultural and material return by discovery and by stimulus to other discoverers; but one might as well take the spade from a gardener as a reasonable degree of seclusion from a research worker. If a young scientist's real interest is seen to lie in politics, one has but a single duty to him and to the community: he should be encouraged to enter politics. Science will survive only if it is served by those whose true interest is the search for truth.

Despite the obvious difference in outlook between the scientist and the politician, it is becoming fashionable to urge scientists to study politics and to express surprise that there is only one scientist in the House of Commons. Scientific knowledge is not so important for administrators as might be thought. Administrators and members of the government should have a scientific background, a knowledge of the value, spirit and method of science; but they need not be scientists. A non-scientist who has seen a man die of phosgene poisoning is as good a judge as the most expert chemist or pathologist of the desirability of the use of gas in warfare. Scientists who take to politics are apt to leave the scientific method behind them in their laboratories, and immediately begin to use phrases and slogans of a looseness and incomprehensibility which would shock them to the core in their proper subjects. Thus, they will write glibly of our "governing class", as though those two words conveyed any intelligible meaning in present-day Britain. Waddington leaves

his laboratory and proceeds to tell us that living things grow, reproduce and evolve; that these are processes, not "static things"; that only Marxists have really taken notice of these facts; and that if anyone does take notice of them, he is an adherent to the Communist doctrine of dialectical materialism. The reader does not need to be told that this is nonsense, but he is asked to refer to p. 81 of Dr. Waddington's book to see that I have not misconstrued what he says[139].

In his history of technology, to which for some inexplicable reason the name of "The social relations of science" is attached, J. G. Crowther[26] pours scorn on people who, according to him, regarded certain lines of investigation as "respectable" and others as "socially disreputable"; but he does not realize that in putting all the emphasis on the applications of science he himself is trying to make a part of science—the most solid and fruitful part—"socially disreputable". He claims that "the greatest service that can be rendered to science in a period of crisis is to assist the struggle of the progressive class for power". On the contrary, the greatest service that can be rendered to science in a period of crisis or at any other time is to give opportunity to those talented people, of either sex, of every class, of all races, of any religion or none, who have that genuine urge to find out and generalize which is the basis of discovery.

Chapter 3

Individualism in Science

> "*The grand, leading principle, towards which every argument unfolded in these pages directly converges, is the absolute and essential importance of human development in its richest diversity.*"
>
> WILHELM VON HUMBOLDT[76]

IN the past, all reformers have been anxious to improve the lot of the less fortunate members of the community, and they have wished to do so by spreading freedom more widely. Now a new kind of reformer has sprung up, who wishes to improve the lot of the community by the opposite process of taking freedom away. In the past, the progressive has always worked for freedom; now, the reactionary agitator pretends to be a progressive. It is an astonishing fact that even science has provided its quota to the ranks of those who are bent on reducing freedom, and more astonishing still that even the reduction of freedom in science itself is contemplated.

J. G. Crowther[26] writes that a factor disposing scientists to acquiesce in dictatorship is their habit of accepting authority in their own work. This is a strange statement. Scarcely a single scientist in any part of the world will agree that scientists in general are so disposed, for science is precisely that subject in which authority counts for nothing. The motto of the Royal Society (*Nullius in verba*) states this explicitly, and every scientist knows that discoveries must be demonstrable, for no one will take them on anyone's authority.

As Bertrand Russell has said[118], men who like administration think that it is good for the populace to be treated like a herd of sheep. Nowadays there are those who think it good not only for the populace but also for scientific research workers. This is the message of Bernal's "Social function of science"[15]. Anyone who reads this book must become aware that it preaches a doctrine of the reduction of freedom for research workers. It is true that here and there the book contains passages which pay lip-service to the ideal of freedom; but these passages are contradictory to the whole tenor of the book.

Bernal does not stand alone. Waddington[139], who tells us three times in a small book on "The scientific attitude" that totalitarianism is bound to come to Britain, is faintly in favour of individualism on one page and faintly opposed to it on another. He tells us on one page that communism is "near" to science, and on another that for communism the final test of value is not critical experiment but service to the interests of a particular class of the community; loyalty to that class is more important than truth. What "near" means under these circumstances, it is impossible to guess. It is only fair to say that Waddington admits the necessity for every scientist to be free to disagree with the majority, including his elders and betters. Scientific progress, as he says, would come to a "fairly immediate" end if that were not allowed.

J. G. Crowther[26] suffers from none of Waddington's nice hesitations about ushering in the totalitarian régime for scientists. He discusses whether freedom is better or worse than an inquisition instituted to make sure that scientists hold the proper political views. He finds nothing good or bad about freedom or inquisition in themselves, but claims that whichever of them supports a progressive class is good. Scientists must therefore be subjected to a political inquisi-

tion if that serves a particular class of the community which is called "progressive". What godlike creature decides whether a given class is progressive, we are not told. The reception of this book shows that there has been an extraordinary change in people's attitude to liberty. In 1916 R. A. Gregory wrote a stimulating book[55] on the true spirit of science. "The men who have advanced the human race throughout the ages", he said, "are those who have stood for individuality as against the conclusions of the crowd." A quarter of a century later, now Sir Richard Gregory, F.R.S., President of the British Association for the Advancement of Science, he writes a favourable review[56] of Crowther's book.

As contempt for liberty grows, so everything that distinguishes one person from another becomes a subject for scorn. "Originality", as J. S. Mill wrote[98], "is the one thing which unoriginal minds cannot feel the use of." Not only can they not feel the use of it: they hate and fear it. Geniuses are "more individual than any other people—less capable, consequently, of fitting themselves, without hurtful compression, into any of the small number of moulds which society provides in order to save its members the trouble of forming their own character"[98]. Compression is hurtful in science not only to geniuses, but to those other talented people who differ from them, as we have seen (p. 37), not in kind but only in degree.

The danger of the threat to individualism has already been recognized in the arts. Sackville West writes[143] that he hopes that "ill-health or other extraordinary circumstances" will keep some composers apart from the unified stream of contemporary life, so that there may be Chopins and Brahmses in the future. One agrees that ill-health is a small price to pay for that; but it is a striking commentary on present-day life that the mania for uniformity should

create a wish for someone's ill-health, so that he can develop his own personality and produce good music. For myself, I heartily wish all my colleagues (and myself) ill-health, if that is the necessary price for permission to live and serve the community as individuals.

Every scientist benefits from the work of others, either by personal contact or by reading. The contact between scientists is necessarily somewhat closer than between artists or composers: it is more important for them to keep in touch to some extent with what others are doing (though when this is overdone, originality wanes). Few things in life are so stimulating and productive as discussions between scientific colleagues. Sometimes two or three will find it helpful to work together for a time. This is a very different thing from dictated team-research. Anyone who has had long experience of undergraduates in a honour school of science knows that they may be roughly classified in two groups. One lot—the majority—are not fertile in ideas, and when they have got their degrees they are happy to take their places in a team, and will do very useful work in it. These men are often talented, and it would be far from my intention to try to belittle them or pretend that they do not make contributions to knowledge. The other lot consists of the born investigators. One sees them from their early days in the university, bubbling over with ideas for research, in trouble rather from the profusion of attractive subjects for investigation than from incapacity to think of anything to study. To talk to them is to be stimulated. To force them into a team or to make them follow slavishly someone else's ideas would be like harnessing race-horses together to pull a plough, or taking fighter-pilots from their aeroplanes to man a cargo-vessel. It is absurd to pretend that these men are selfish because they want to follow their own bent; other scientists are in their debt for the stimulus they

impart to all with whom they come in contact. They embody the living spirit of discovery. Let them work by themselves, or collaborate for a time with equals, or draw a group of fresh young minds round themselves if they wish; but let them be free, for freedom is necessary for the development of their talent.

It would be unnecessary to say all this, if there were more understanding of the human nature of the born investigator; but alas! the general average of mankind, as J. S. Mill wrote[98], "are not only moderate in intellect, but also moderate in inclinations: they have no tastes or wishes strong enough to incline them to do anything unusual and they consequently do not understand those who have". If science is to survive, it is essential for people to understand that the real investigator must have freedom or his genius will wither.

People have tried[89] to equate individualism with the survival of the fittest, as though the only original thing an individual could think of doing were to gain an advantage over someone else. What a travesty of the facts! Listening to the work of a great composer, looking at a great picture, reading a great piece of literature, studying the results obtained by a great scientist, one is sincerely grateful that the person to whom one stands in such irredeemable debt was able to develop his own individual personality and was not forced by the severities of convention to stand at the same dull average level as the community as a whole. The modern tendency to confound individualism with selfishness, and collectivism with generosity, would be funny if it were not a real danger to civilization. Nothing is more selfish than finding happiness in the direction of the lives of others, nothing more generous than the wish that all should be free. Let those who pretend that individualism is selfish ask themselves whether they find generosity in the

concentration camps, purges and so-called "trials" of totalitarian states.

It is instructive to make a comparison between scientists and soldiers. In an army the best-informed person is supposed to be the general, who deputes duties less important than his own to colonels, and these do likewise to majors, and so on through captains and lieutenants and the various non-commissioned ranks down finally to private soldiers, who form the largest and lowest group of all. In the world of scientific research we must equate the investigator with the private soldier and lance-corporal, the latter rank only appearing when a few scientists agree to work together with one of their number as the main animator of the investigation. (I leave out the laboratory assistants, not because I underrate their great services, but because they are generally fewer than the research workers and thus confuse the simile.) If research were dictated from above, there would have to be higher ranks, all the way up to generals. This would lead to absurdity. No born investigator would ever agree to rise above the rank of lance-corporal and thus voluntarily become a petty little scientific dictator while depriving himself of the one thing he values above all else in life, the actual doing of research. All the higher ranks would have to be filled, therefore, by people who are not first-rate research workers. To imagine that the true investigator would work under their direction is equivalent to imagining that a composer would agree to put his notes where a less talented person thought fit. The whole idea of dictated research is fantastic, because the people best qualified to be generals would insist upon being lance-corporals. There can be no hierarchy in research.

So long as science contains only lance-corporals and privates, there will be no interference with research. Karl Darrow, of the Bell Telephone Laboratories, has put this

matter succinctly[32]. He says that the essential requirement for the development of physics in particular and science in general is "a supply of talented people enabled and permitted to go their own ways, so that discovery may occur in whatever logical or capricious or ironical ways may be chosen by destiny. Non-interference is essential". It is essential because discoverers must be free gradually to develop their talents and move from topic to topic and even from subject to subject as their experience develops.

The development of experience can be illustrated by the life of Pasteur, who never suffered the indignity of having the subjects of his research dictated to him by others, but moved freely forwards through a wide series of investigations, each suggested by the one that went before. Starting with the study of the forms of the crystals of tartrates, he finds that one tartrate will undergo fermentation if infected with albuminous matter, while another, differing only as left from right, will not. He leaves crystal structure, having made an enormous contribution to that study, and passes to the investigation of fermentation, at that time so little explored. He works at the fermentation of milk and the resulting formation of lactic acid, and makes the illuminating discovery that bacteria are the cause of the chemical change. He passes to the question whether bacteria can originate from inanimate matter or only from pre-existing bacteria, and draws the latter conclusion. From this momentous work he passes to severely practical issues, the rôle of micro-organisms in the vinegar and wine industries, and afterwards from the diseases of wines to those of organisms. Having shown that micro-organisms can cause disease in silkworms, he passes to methods of counteracting their harmful effects. He discovers that the germ of chicken cholera can be rendered less virulent, while retaining its capacity to give immunity to fowls against the virulent form of the disease.

He applies this method to the prevention of anthrax in sheep and cattle, and passes lastly to his crowning practical achievement, the conquest of hydrophobia. So, by a roundabout route, Pasteur passed from crystallography to immunology, and from one epoch-making discovery to another. Never did anyone try to confine his attention to set subjects.

Let us compare Pasteur's freedom with the shackles surrounding the research worker in a totalitarian state. In Soviet Russia[26] a research worker cannot change his subject without wide discussions with the rest of the staff of his institute, and an individual's personal desires as to what he wants to work at receive little consideration. Research workers are organized in brigades. There is little cause for surprise when even a convinced admirer of the Soviet régime has to admit that "it would be idle to look for the quietly pursued excellence and sound and acute scholarship" in the U.S.S.R.[16]. Bernal may make what excuses he likes for his protégés, but it will not alter the fact that quietly pursued excellence and sound and acute scholarship are precisely what we should look for everywhere in science. If scientists of the future are everywhere organized in brigades, and little consideration paid to the desires of individuals as to what they want to study, then genuine investigators will fit up primitive little laboratories in attics and sheds, and the great discoveries of the future will be made at home.

It is a striking fact that even in communities where the supposed welfare of the state is made the supreme consideration, the authorities dare not ignore the existence of the individual. When Maria Utkina, unaided, destroys a Panzer formation or performs some other commendable military exercise, we are told very particularly in the Soviet communiqué that it is Maria Utkina herself who did it. There is an inherent recognition of the fact that even in a

totalitarian state, potential Maria Utkinas appreciate the performance of an individual.

The forcing of research workers into brigades is a deprivation of their rights as individuals, but an even more intolerable proceeding would be the amalgamation of all the scientists in a country into a single body intended to get power by the threat of striking. The question of the advisability of a strike by all the scientists in our country is seriously discussed by J. G. Crowther[26], who does not realize that no section of the community is less interested in possessing power than the genuine investigator. One has only to think of the great scientists of the past and present and of the stimulating personalities among one's own scientific friends and colleagues, to realize that petty struggles for power would be beneath their contempt; and they would consider it nothing short of idiocy voluntarily to deprive themselves by striking of the thing above all that makes their lives seem to them worth living, the right and duty to discover truth by free enquiry.

Free enquiry is just as important to the scientist as freedom of speech and publication. This point is so obvious that it might be thought scarcely worth mentioning, but in fact it is very important to mention it. Many people who talk airily about the necessity for freedom in science are actually thinking only of the freedom of scientists to say and write what they like. That is a relatively small freedom, if they are not allowed to investigate what they like and therefore to make discoveries which are worth talking and writing about. There is a movement on foot to try to get university laboratories to undertake research on stated problems after the war. This is a real threat to freedom. A biologist might wish and feel himself fitted to devote himself to research on, e.g., cell-chemistry, but his university department might be allotted the task of discovering how to

induce the larvæ of clothes moths to make fewer or smaller holes in clothes. It would be no good to say to that man, "My dear sir, you are perfectly free: you can publish whatever you like on cell-chemistry or politics or anything else." The man would answer, "I want to publish on cell-chemistry, if I can make discoveries in that subject, as I have reason to believe I can. If I may not work on that subject, my freedom to publish about it is illusory." The negation of freedom is implicit in the suggestion that science should be centrally planned.

On 28th September 1941 the President of the British Association announced at the Royal Institution, London, a "Charter of Scientific Fellowship". The second word is freedom and the necessity for liberty is re-iterated, but it is clear that those who drafted the Charter had freedom of speech and publication, and not freedom of investigation, in mind. The people who wish to see science planned seem to have had such an unfortunate influence on those who drafted the Charter, that its preamble and seven clauses contain nothing to suggest that any scientist anywhere should have the right to decide what he will investigate. Freedom of thought and its expression serves the philosopher and writer well: it is not sufficient for the scientist, who wants to find out first and talk afterwards. True freedom is not granted by this charter, but it is a cardinal part of the requirements for liberty laid down by the Society for Freedom in Science. One of the five propositions to which members of that Society adhere is this: "The conditions of appointment of research workers at universities should give them freedom to choose their own problems within their subjects and to work separately or in collaboration as they may prefer. Controlled teamwork, essential for some problems, is out of place in others. Some people work best singly, others in teams, and provision should be made for

both types." These few unequivocal words are worth more than any amount of loose talk about freedom.

If the community were to decide that all research workers must contribute directly and obviously to material human welfare, they could be required to spend part of their time on manual or other labour. Already the majority of research workers spend a large part of their time in teaching or in other work in which complete freedom is impossible. (Lecturers, for example, must give their lectures on appointed subjects at appointed times.) If this were not considered a sufficient direct contribution to material welfare, the community would be far better advised to make research workers do a certain amount of manual labour and leave them free in their research periods, than to conscribe them into planned research.

In special research institutions it is reasonable to require people to undertake the sort of research for which the institution was founded. For instance, a scientist who has freely joined a marine biological laboratory may properly be required to devote his attention mainly to research in marine biology. When a research worker does no teaching or consultation but devotes the whole of his time to research, it is not unreasonable to require him to spend a part of his time in working on a subject selected by the director of the institution, provided that he is free during a substantial part of his time. With these and similar exceptions the utmost freedom is desirable, and it scarcely needs to be said that under all circumstances the investigator should be free to publish his results, whatever they may be.

It is fashionable to set up an Aunt Sally of individualism in order to knock it down. When great power is placed in the hands of single persons, they often use it to the detriment of others; and a baseless hatred of individualism has grown up because of this and as a result of envy and jealousy.

Those who would use their rights as individuals to the greatest benefit of the community as a whole—the composers, artists, writers and scientists—are the very people to whom power means least and who are the least likely to wish to hold others in subjection. To deny individualism to the creators of culture would be to make their work impossible; to do so on the ground that lovers of power misuse it would be absurd. Creative thinkers do not desire to control but only to serve humanity. It is vital to civilization that true individualism should survive and be saved from confusion with the personal love of power, with which it has nothing in common. "Whatever crushes individuality", a great philosopher has written[98], "is despotism, by whatever name it may be called."

Those who care nothing for freedom try to confuse the issue by saying that the urgent freedoms are freedom from want and freedom from fear. This obvious and self-condemned attempt to evade the issue should deceive no one. Freedom from want and fear is intended to mean absence of want and fear. Everyone desires an absence of what is obviously undesirable. Freedom means nothing negative. The word implies the positive right of individuals to choose for themselves between different possibilities of action.

Chapter 4

Planning in Science

"*Le hasard ne favorise que les esprits préparés.*" PASTEUR[136]

WHEN it is proposed to build a house, a plan is drawn. That is because it is possible and necessary to envisage the final form of the house before building it. It is precisely because the whole purpose of science is to discover that which is not and cannot be envisaged, that planning in science is self-contradictory; it is as though explorers were to map an unknown country before they had reached it.

Today there is a resurgence of an old idea that almost anyone can be machine-finished into a scientist and that advances in knowledge can be turned out automatically like sausages from a machine. Those who want to plan science go back to the sixteenth and seventeenth centuries to find their hero in Francis Bacon, than whom a more unsuitable object for heroics can scarcely be conceived. Those who see in him the prototype of that modern repository of virtue, the politically-minded planner of science, should know that Bacon's interest in politics was fostered solely by his desire to gain worldly power. He obtained the personal advancement he so much desired by concealment of his own opinions and by flattery. When it suited his convenience, and power was in his hands, he turned savagely against those who had befriended him. It is strange indeed that those who think themselves revolutionary in politics should admire Bacon. When an old clergyman wrote a sermon justifying insurrection under certain circumstances, Bacon was active in his

prosecution, though the matter was never preached or published. He questioned the old man under torture, and visited each judge of the court separately in private, to secure conviction. One so obsequious to the king as Bacon is a queer hero for modern times. His conviction for taking bribes to influence the course of justice in lawsuits ended his public career.

When all this has been said, it remains true that Bacon could be respected if his scientific work were respectable. It has been pointed out, however, by a historian of physics[20], that he "was not a scientific man; he had little practical experience in experimentation; he lacked the scientific instinct to pursue in detail the great truth that nature must be studied directly by observation and experiment". Bacon thought he could make almost anyone into a scientist, for his method "nearly levels all wits and intellects"; he would have been surprised if he had been told that three centuries later a scientist would write of his method that "no evidence can be shown of its successful application in any branch of science"[19]. Draper[39] says of him very simply that he was "a treacherous friend, a bad man", whose admirers have thought that scientific discoveries are accomplished by a mechanico-mental operation. Oliver Lodge[88] said that "on the solid progress of science he may be said to have had little or no effect". Andrade[6] says that he was "a stranger to quantitative work, and he had an aversion from the method of the working hypothesis, to which science actually owes its advances. . . . he could not recognize real scientific advances when he saw them".

Bacon's writings contain a mass of ill-digested and disconnected statements about natural objects and phenomena, with suggestions for experiments but little evidence of a desire to try them himself. His "Sylva Sylvarum"[137] is scarcely readable, so full is it of uncritical statements, errors,

capricious formulae and platitudes. "A *Man Leapeth* better with *Weights*, in his *Hands*, than without. The *Cause* is, for that the *Weight*, (if it be proportionable,) strengtheneth the *Sinewes*, by *Contracting* them." "A *Dry March*, and a *Dry May*, portend a *Wholsome Summer*, if there be a *Showring April* between: But otherwise, it is a *Signe* of a *Pestilential Year*." "It is true, that the *Ape* is a Merry and Bold *Beast*. And that the same *Heart* likewise of an *Ape* applyed to the *Neck*, or *Head*, helpeth the *Wit*; And is good for the *Falling-Sicknesse*." It is strange to reflect that this book was written by one who ignored Harvey and Kepler, rejected Copernicus, and did not appreciate the achievements of Gilbert and Galileo. It is stranger still that some people should derive the methods of modern science from him rather than from them. His guess about the nature of heat was not a discovery in any scientific sense, and anyhow a very similar guess had been put forward by Plutarch more than a millennium before[144].

The idea of planned research originated in Bacon's "New Atlantis"[138]. This is an imaginary story of the author's visit to an unknown island called Bensalem in the Pacific Ocean. His ship had sailed from Peru for China and Japan, but was delayed by contrary winds. The ship's company ran short of food and had given themselves up for lost, when they sighted an island. Here they were most hospitably received by the inhabitants, who had had no visitor from the outside world for thirty-seven years, and very few for many centuries past. In ancient days the island was known to the other parts of the world, but about 300 B.C. the great king of Bensalem, Salomona, decided that contact with strange lands should be almost completely avoided, as he thought it difficult to derive benefit from receiving strangers. Twenty years after the death of Christ an enormous apparition of God's finger converted all the inhabitants to Christi-

anity, and a cedar box was conveniently sent, containing the whole of the Bible, including the parts which had not then been written. The people became extraordinarily virtuous in all respects and remained so down to the time of the author's visit.

The author was chosen from the whole of the ship's company for the very special privilege of visiting the head or "Father" of a gigantic technical college called Salomon's House, which had been instituted by the great king who first caused the island to be isolated. Salomon's House extended vertically from towers half a mile high to caves three miles below the surface of the earth. Its charter was a worthy and dignified one: "*The end of our* Foundation is the *Knowledge of* Causes, *and Secret Motions of things; and the Enlarging of the bounds of* Humane Empire, *to the Effecting of all things possible*." In this college the principles of planned technology were carried into effect. Little was done in pure science, whose study was confined to three "Mystery-men". There were "Particular Pools" where "Trials *upon* Fishes" were made, and "Perspective-Houses" for optical experiments; but beyond this most of the work was in technology. After meetings and consultations of all the investigators, three special Fellows devised new experiments for others to undertake. Each Fellow had his job: some were professional students of the literature of the subjects investigated at the college; others were explorers, charged to reside abroad for twelve years at a time, concealing their place of origin, and to bring back information about foreign technology and sciences. The experiments were concerned with remarkable enquiries. Some applied themselves to perfect the water of Paradise, "*very soveraign for* Health *and* Prolongation *of* Life". Others concocted "Drinks *of* Extreme Thin Parts; *To insinuate into the* Body". Others again worked to "Multiply Smells", which, as the author justly

remarks, "*may seem strange*". Yet others "*represent all manner of* Feats *of* Jugling". Among their laboratory conveniences were "Heats *of* Dungs, *and of* Bellies *and* Mawes *of* Living Creatures".

The story ends abruptly when the author had been told about the marvels of the Academy, but had not himself seen them; for "New Atlantis" was never finished.

Salomon's House lends itself to satire, and it is probable that Swift's Academy of Lagado[124] is a skit upon Bacon's idea. It will be recollected that when Gulliver is let down from the flying island of Laputa and reaches the earth near the city of Lagado, it is not long before he is taken to see the wonders of the Academy. It is amusing to read the "New Atlantis" first, and then turn straight to Chapters 5 and 6 of the Laputa voyage, in which the visit to the Academy is described. Swift is here in his most satirical vein. The modern exponent of the elaborate card-index and other mechanical devices for enabling anyone to make discoveries automatically finds himself already satirized long before his birth. A professor of the academy tells Gulliver that everyone knows "how laborious the usual method is of attaining to arts and sciences"; and he explains his mechanical contrivance whereby "the most ignorant person, at a reasonable charge, and with a little bodily labour" can write books on any subject "without the least assistance from genius or study". Even Swift's vivid imagination scarcely sufficed to make the employments of the professors at the academy more fantastic than those which occupied the attention of some of the Fellows of Salomon's House.

Bacon was no scientist and did not understand the conditions under which research can be carried out. Nevertheless, there are a few things that stand directly to his credit. He strove to overthrow belief in the ultimate authority of Aristotle. He was far before his time in his attitude to

teleology. In "The advancement of learning"[9] he shows that little help is given by statements that the eye-lashes are intended to protect the eyes, or skins and hides to defend from heat and cold, or bones to form frames for living creatures, or clouds to water the earth. The search for physical causes, said Bacon, "hath been neglected, and passed in silence", because the teleological explanations have acted as hindrances. This is sound sense, if not pushed too far. Better still is one inconspicuous remark in "New Atlantis". When describing the functions of the various Fellows of Salomon's House, he tells of three who differ markedly from all the others. In the words of the Father of the House: "*We have Three that trie* New Experiments. *Such as themselves think good. These we call* Pioneers *or* Miners." Much can be forgiven to Bacon for those eighteen words. Science was not quite dead even in the metropolis of planned technology.

The fundamental reasons why science cannot be comprehensively planned are two. First, scientists are not, and cannot be replaced by, crude machines, a fact that has been sufficiently emphasized in the foregoing chapters. Secondly, discoveries often come by way of surprise, and not as a result of meticulous attention to a plan; for the end of a research cannot be envisaged when the plan is being made. If a scientist is working along a line of his own, and suddenly an unexpected vista opens before him, he will often arrive at important results through having the necessary insight and mental energy to throw over his plan and follow the new trail[10] Chance plays a large part in discovery, much larger than people are apt to think; but chance, as Pasteur said, "only favours prepared minds"[136]. It is not the slave to a plan, but the person with the mind that is prepared for the unexpected, who becomes the great discoverer.

The discovery of current electricity was made by that

fruitful combination, chance and a prepared mind. Galvani was not a physicist, but a professor of anatomy at Bologna. In his experiments on muscles removed from recently-killed frogs, he sometimes noticed unaccountable twitchings, not attributable to any obvious mechanical stimulus. He experimented for several years on frogs' legs suspended on wires and hooks, and at last discovered that the twitchings were caused by the accidental touching of one part of the preparation by a piece of iron and another by a piece of copper, the iron and copper being themselves in contact.* Galvani had seen similar twitchings produced by electrical machines, and he thought there might be an electrical explanation[2]. It was true: he had accidentally made a primitive electrical cell. His observation led to the understanding of current electricity and to the invention of the voltaic cell by Volta.

Von Röntgen had no thought of trying to make human flesh transparent when he discovered the penetrating powers of X-rays. He was interested in the phenomena of electric discharge in high vacua, and did not guess that the result of his work would be the discovery that certain rays could be used in the diagnosis and treatment of human illness. As he afterwards said himself, "I found by accident that the rays penetrated black paper." He had been using barium platinocyanide with the object of detecting invisible rays, but with no thought of such rays being particularly penetrating. He left some of this substance on a bench near his vacuum tube, and chanced to notice that although the room was dark and there was black paper in between, the barium platinocyanide became fluorescent[10, 52]. From the time of seeing the fluorescence von Röntgen isolated himself for three weeks, working at high pressure without discussing the phenomenon that he had witnessed with anyone. At

* Another explanation of Galvani's results is possible.[146]

first he ate and slept in the laboratory. As Gregory has written[55], "After the discovery of Röntgen rays, their application to medicine was soon seen." "After" is the key word.

Von Röntgen's discovery displays two quite separate aspects of the action of chance in science, for it illustrates unexpectedness both in discovery and in the applications of discovery. In the first place, the original discovery in pure science—the discovery that the rays are particularly penetrating—was made quite by chance, owing to some barium platinocyanide happening to be in the vicinity of the vacuum tube. In the second place, it was by chance and not by plan that medicine was so enormously benefited. If someone had thought it would be convenient to make the human body transparent, and had allocated money for the research, the result would have been a comprehensive plan, a team of research workers, a very large card-index, a waste of money, and no X-rays. Von Röntgen wanted no team and no planner's plan. He wanted to make his own studies of electric discharge in high vacua and he wanted to work alone. Not only did he not want a single colleague in his laboratory: he did not even want a laboratory assistant unless a piece of apparatus required the use of more than two hands, or his green-colourblindness necessitated outside help. He preferred the undisturbed atmosphere of solitude during his research[52]. Not many men have done more for pure science or for the relief of suffering than von Röntgen.

In the pages of this chapter and the next a few instances out of a multitude are given of the action of chance in science. One might have given examples of its action in discovery first, and then passed on to examples of the unexpectedness of the applications of discoveries to practical affairs, but it has seemed best to consider both kinds of chance together. Often the two kinds are woven together,

as in the discovery and application of X-rays and of the relation between electricity and magnetism.

It was the happy combination of chance and a prepared mind that disclosed the relation between electricity and magnetism in 1822. Because he chanced to hold a wire carrying an electric current over a magnetic needle, Oersted stumbled on his epoch-making discovery. It was of this particular event that Pasteur made his remark about chance favouring the prepared mind. The converse discovery by Faraday, that a magnet can cause an electric current to flow, illustrates with overwhelming force the unexpectedness of the applications of science. If we ask ourselves what scientific discovery has, more than any other, changed the face of civilized life in a material way, we are likely to answer the discovery of electro-magnetic induction. The basic fact that the movement of a magnet in the vicinity of a coil of wire produces an electric current was made by Faraday as a contribution to pure science. The electrical, motor-car and aeroplane industries depend for their existence upon that discovery. Its huge applications render all the more amusing the memorable incident which occurred when Faraday had just delivered a public lecture on the subject. A woman in the audience asked Faraday what was the use of his discovery. If she could live today and see what have been its scientific and practical results, she would blush with shame every time she remembered the incident. In this age, when real science is threatened by those who vainly pretend that discoveries come only in direct response to human needs, it is exhilarating to recall Faraday's answer, a repetition of what Franklin had said in similar circumstances long before[136]. "Madam," asked Faraday, "will you tell me the use of a new-born child?"[55] The history of electromagnetic induction exposes as clearly as X-rays the lie that necessity is the mother of invention.

Gregory[55] has told how the readers of an American magazine were asked to choose by vote which were the seven most marvellous discoveries and inventions of the modern world. The readers chose wireless telegraphy, the telephone, the aeroplane, radium, antiseptics and antitoxins, spectrum analysis, and X-rays. As Gregory pointed out, each of these discoveries and inventions had its foundations in pure science and was not the result of deliberate intention to make something useful.

The history of the microscope shows convincingly how love of knowledge, quite apart from practical applications, is the driving force behind the progress of science. Anyone who follows the evolution of the compound microscope from its invention by Janssen in 1590[38a] to the magnificent instrument of modern times knows that all along progress has been due to the desire to see the ultimate detail of small objects more clearly for the sake of increasing knowledge. The turning of the instrument to use in industry followed far behind its development for use in pure science. One of the landmarks in its history was the discovery by a wine-merchant[53], Joseph Jackson Lister, that two separate compound lenses could be put one behind the other to form a new sort of high-power object-glass in which the error called "spherical aberration" was largely abolished. Lister was an amateur microscopist, yet his invention ranks in importance with Dollond's discovery of how to minimize colour-fringes and Abbe's magnificent achievement in almost entirely eliminating them by means of his "apochromatic" object-glasses[115]. Abbe's heart and soul were in the improvement of the microscope. The motive of commercial profit did not count with him, and he generously renounced the ownership of his optical works in favour of his employees. Students of the minute plants called Diatoms were always anxious to get the best possible instruments so as to see the

striations and dots on their siliceous shells that are the ultimate test of the resolving power of microscopes. Computers and manufacturers strove always towards perfection: the "Diatom-dotters" would be satisfied with nothing short of the best. The Managing Director of the largest firm of microscope manufacturers in Britain has said[141] that the greater part of the evolution of the modern microscope is to be attributed to the Diatom-dotter. A combination of inventors like Lister and Abbe with enthusiastic observers of microscopic life produced, through love of the subject, the wonderful instrument that we know today. That instrument is at the service of industry, and its material value can scarcely be exaggerated; but the many industries which now profit from its use did nothing to help its development.

Chapter 5

Planning in Science

continued

IN the preceding chapter a few instances have been quoted to show how important the rôle of the unexpected has been in physics, both in discovery and in the applications of discovery. Innumerable instances could be chosen from other sciences. The discoveries of aniline by Unverdorben, of benzene by Faraday and of chloroform by Soubeiran were instanced, among others, by Crookes as the work of men who "seemed at the time never likely to be of the slightest use to anybody"[25]. Such men revolutionize the material welfare of society, while those who follow a plan to improve what already exists plod slowly forward. Science progresses by work in fields whose applications cannot possibly be envisaged. When Wollaston discovered the elements palladium and rhodium, how could he have guessed that the one would find practical application in toning solutions used in photography and the other as a platinum alloy in thermocouples, both photography and thermocouples being concepts of a later period?

People who are not themselves connected with scientific research would be apt to imagine that a substitute for sugar would be discovered by a research undertaken for the purpose of finding a substitute for sugar. That is not how things happen, or can happen, in science. The discovery of saccharin provides an outstanding example of the function of chance in discovery. Remsen and Fahlberg[112] had no thought

of discovering a substitute for sugar when they made their investigations. Their object was purely academic. They wanted to know whether it was possible to make orthosulphobenzoic acid from orthotoluenesulphonic acid. Before this was done, a successful research by another worker on a closely related subject caused their project to lose much of its importance and interest, but they decided to persevere and produced what they called benzoic sulfinide. There was nothing to suggest that their research would have practical applications, until someone tasted the product. "It possesses *a very marked sweet taste*", they wrote, "*being much sweeter than cane-sugar*. The taste is perfectly pure. The minutest quantity of the substance, a bit of its powder scarcely visible, if placed upon the tip of the tongue, causes a sensation of pleasant sweetness throughout the entire cavity of the mouth." They had discovered saccharin. The present-day product differs only in the addition of another substance which, though itself less sweet than saccharin, increases the sweetness of that substance still further[131]. Perfectly pure saccharin is already five hundred times as sweet as sugar, and Remsen and Fahlberg did not exaggerate when they marked their surprise by the italics given in the passage quoted above.

Chemistry provides many examples of the action of chance, but none perhaps more striking than that on which the synthetic dye industry is based. W. H. Perkin, senior, when only eighteen years old, tried to produce quinine synthetically by the oxidation of allyl-*o*-toluidine by potassium dichromate[64]. He failed, but thought it might be interesting to find what happened when a simpler base was treated with the same oxidizer. He chose aniline sulphate and obtained a black precipitate. This included a purplish substance, which was found capable of imparting its colour to silk. Perkin had discovered the first aniline dye. The

whole of the vast synthetic dye industry was built on that discovery; and Perkin was not investigating anything connected with colour when he made it. Chance played an even bigger part in the discovery than the bare facts might indicate, for he would never have discovered aniline dyes if his aniline had been pure. By good fortune it contained some *p*-toluidine, without which the reaction could not have occurred.

A little more than a century ago, when Daguerre was making his attempts to fix the visual image which could so easily be thrown on a screen by a lens, he tried using iodized silver plates, because he knew that silver iodide was sensitive to light. He discovered accidentally[95] that the exposure of his iodized silver plates to the fumes of heated mercury produced a light-sensitive material which gave a fixed image of the object focussed by the lens. Thus the first kind of photography was born—by accident.

Chance often starts a scientist on an investigation which he would not otherwise have undertaken. It appears that the first catalogue of the stars owed its existence to the sudden appearance of a new star during the second century before Christ. This event is said to have influenced Hipparchus, the famous Greek astronomer and founder of trigonometry, to make a list giving the positions of over a thousand stars[54].

Chance started Darwin on his great study of insectivorous plants. In the summer of 1860 he was idling and resting near Hartfield in Sussex[36]. His great work, "The origin of species", had been published the year before, and his mind was ready for a new adventure. It happened that in the neighbourhood of Hartfield two species of sundew (*Drosera*) were abundant. It will be recollected that the leaves of this plant catch and digest small flies. Darwin's attention was instantly attracted: his enthusiasm has been recorded on a previous page (p. 18). The chance presence of sundews

at the place where he took his holiday resulted fifteen years later in the publication of his book, "Insectivorous Plants"[34].

That work of Darwin's was of great interest in pure biology, but did not lead to practical applications. Another botanical study of his, also undertaken purely for its scientific interest, has been fruitful materially as well as academically. The tracing of this subject on its long and unexpected journey from the laboratory of pure science to commercial exploitation shows how unpredictable the course of discovery is, and how destructive it would be to tie research workers down within the narrow confines of a plan. We owe the valuable chemical root-stimulants of today to the research of workers in pure science who were investigating a problem wholly unconnected with the stimulation of root-growth. The subject of their studies was the bending of plants in response to light.

Charles Darwin[36] found that it is the tip of a shoot that perceives the light, but that lower regions, which have not themselves perceived it, bend nevertheless in response. An influence of some kind clearly passes downwards from the tip. In 1913 Boysen Jensen showed than an influence of this kind could pass through plant tissues which he had completely cut across and which were then fixed together with gelatine. This suggested that a substance must pass from the tip through the gelatine to the tissues lower down, which reacted by bending. It was Paál who proved this. Both Boysen Jensen and Paál worked with the seedlings of grasses, the former with the oat, *Avena*, which became the classical object for the study. The young shoot of the germinating seedling is protected by a long, hollow, conical or pencil-shaped sheath. Paál cut this transversely across, as did Boysen Jensen, and then stuck it on again; but instead of sticking it on centrally, as one might mend a pencil

broken in two, he put the detached part back somewhat to one side, so that its base only covered part of the exposed stump.

Now a very remarkable thing happened. An influence passed down from the tip of the detached part into the tissues of the seedling, below where the cut had been made. The influence caused those tissues to grow fast, but it only affected that side above which the cut-off part was re-attached. The result was that growth was greater on one side than on the other, and the shoot began to bend. Paál rightly concluded that a growth-stimulating substance had passed down one side only of the seedling and thus produced asymmetrical growth.

Thus arose the study of plant-hormones[100, 142]. Chemical messengers of this kind, originating in one part of the organism and affecting the growth of another, had long been known in animals: the thyroid, pituitary and reproductive glands are among those which produce them and thus exert powerful influences on growth. In plants they had hitherto been unknown. Now the problem was to identify them. Went proved in 1928 that the substance formed by the sheath-tip, whatever it (or they) might be, was unaffected by boiling and therefore not a ferment. Others sought to find out what substances other than those which originate in the shoot-sheath can permeate plant tissues and influence growth. Strangely enough it was found that human urine contained large quantities of two such substances, "auxin a" and a substance called indole-acetic acid. It would appear that "auxin a" is the main hormone actually produced by the shoot-sheath of the oat, and it seems very extraordinary that it should occur also in urine. Indole-acetic acid was shown to be the very same substance that a certain fungus makes, and it greatly affects the growth of the accepted test-object, the seedling of the oat.

Various people have from time to time tried deliberately, but with little success, to stimulate root-growth, mostly by experimenting on the nutrition of the root. Nutrition would be the obvious subject of the planner's plan, but it was not the solution of the riddle. Bouillene and Went showed in 1933 that the first leaves of seedlings contain a hormone which stimulates root-growth. Substances with the same effect were extracted from various plants, especially the fungus already mentioned. In 1935 Thimann and Koepfli[128] and another independent worker showed that indole-acetic acid, prepared in the laboratory, is as effective as any of the natural products.

The responses of the roots of many plants were now studied. Practical applications were already envisaged in the year of Thimann and Koepfli's discovery, by a worker who tried root-stimulants on plants of commercial importance. Favourable results were obtained and the method has been taken into horticultural practice. The roots of seedlings are treated for a day or less with a solution of indole-acetic acid in water, and a surprisingly prolific outgrowth of rootlets subsequently results. Cuttings may be stimulated to form roots by being smeared with lanolin mixed with a little indole-acetic acid. Thus purely academic investigations of the influence of light on the movements of plants have not only greatly enriched pure science, but also, in the most curiously roundabout manner, resulted in the introduction of a method of direct material advantage to man. Went and Thimann, two of the foremost workers on plant hormones, have themselves pointed out that it was research in pure science that gave the world the practical benefit of root-stimulation[142].

Endless examples of the effect of the unexpected in the promotion and application of discoveries could be quoted from any science. I shall limit myself to a few

more, mostly chosen from the sciences on which medicine is based.

More than half a century ago von Mering and Minkowski were studying the function of the pancreas in digestion. In the course of their work they removed the pancreas from a number of dogs. By an extraordinary bit of good fortune, a laboratory assistant happened to notice something unusual about those dogs: swarms of flies gathered round their urine[23]. Today, thousands of people have reason to be grateful to that laboratory assistant for mentioning it to the investigators. One of them thought it worth while to look into the matter. The urine was analysed and found to be loaded with sugar. Experimental diabetes had been produced for the first time, and an insight given into the cause of that disease. It was not some one working at diabetes who found the cause. The investigators were studying the physiology of digestion, a subject which has no connection with diabetes. From then onwards it was known that the pancreas produced something as well as digestive ferments. That something was insulin, and the problem was how to isolate it. If that could be done, the substance could be injected into people suffering from diabetes. The difficulties were great, because the digestive ferments of the pancreas destroyed the insulin when attempts were made to extract the latter. Banting and Best achieved the first solution of the difficulty[91]. They tied off the pancreatic duct of animals and thus caused the cells which produce the digestive ferments to atrophy, leaving the insulin unaffected and extractable. It would be too troublesome, however, to have to make a major operation on an animal every time one wanted to use its pancreas as a source of insulin, and then wait for changes to happen in that pancreas. With the aid of Collip (see p. 28), they succeeded in making extracts of insulin from ordinary pancreases without any necessity to tie the duct,

extracts so pure as to cause no local irritation when injected into human beings. Insulin enables diabetics to control their illness.

The long researches which led to insulin started from a chance observation. Again and again in science it is a chance observation or even a mistaken idea which leads to great discoveries, not solemn plodding along the dull paths of some one else's pompous and consistent plan. The whole subject of chemotheraphy, with all its enormous benefits to the human race, was founded on a mistake. Paul Ehrlich was interested in the action of dyes in rendering distinct the minute structure of the tissues of animals. In 1886 he gave the formula[42] for a dye solution which is probably to this day more used in biological laboratories than any other. He reflected on the specificity of certain dyes for certain micro-organisms, and thought it possible that a substance might be found which would combine with the protoplasm of the living parasites causing disease without damaging the host tissues. He tried the effects of various dyes on living trypanosomes, those blood-parasites of which some cause sleeping sickness in man and other nagana in cattle. In 1906 he found that trypan violet was effective in the way he had hoped[127]. This discovery was the origin of chemotherapy. The dye was itself too harmful to the host to provide a solution to the problem, but it was more harmful to the parasites. Ehrlich now tried a different but related kind of drug, differing mainly in that two atoms of arsenic replaced two of nitrogen in the central part of the molecule. The result was "606", which, with the related drugs that followed it, has been so enormously effective against syphilis. Thanks to them, it is not easy today to find a fully-developed case of the disease to show to medical students. Sleeping sickness fell to tryparsamide, and the diseases due to trypanosomes and spirochaetes were no longer the menace they had been. This huge

success was founded on an error, for Ehrlich's idea, that the drugs would act on micro-organisms as a dye on wool, was wrong. Various theories of their mode of action are held today, but Ehrlich's is not among them[127]. A very great man, following a false clue, became one of humanity's greatest benefactors.

The organic arsenical drugs which owe their existence to Ehrlich are not effective against the diseases caused by bacteria, and blood poisoning, puerperal fever, gonorrhoea, etc., remained the scourge they had always been. Today those diseases are under man's control, thanks to the following up of another false clue by another great man, Gerard Domagk.

Domagk was impressed by Ehrlich's early work, and tried the effects of a great number of dyes belonging to the group called "azo-dyes", to which Ehrlich's trypan violet belonged. It was in 1932 that the great discovery was made. A drug was found which killed streptococci without killing the mice they parasitized. In 1935 the azo-dye, prontosil, was put at the disposal of medical men all over the world and a new era in medicine was opened. the era of the attack on bacteria by chemotherapy. Puerperal fever, blood-poisoning, erysipelas, pneumonia, cerebrospinal meningitis and gonorrhoea began to fall before the series of drugs related to prontosil. Yet the clue to this great discovery was false.

Domagk worked with azo-dyes, which are complicated chemical compounds characterized by the presence of two nitrogen atoms in the middle of the molecule. It is the presence of these two nitrogen atoms, linked together and to the rest of the molecule in a special way, that confers colour on the azo-dyes. Prontosil itself is red. Remove the azo-linkage from an azo dye, and colour is destroyed. Domagk did not break the azo-linkage, which he thought necessary for the action on bacteria. Very shortly after Domagk's work

was made public, four French workers published a little two-page paper[134] which threw an entirely new light on the subject. They tried the effect of one end only of Domagk's molecule, without the azo-linkage. This end, by itself, is sulphanilamide, a substance which is colourless and much simpler than prontosil. They injected the hydrochloride of this base into six mice infected with streptococci taken from a woman who died of puerperal fever. There was a marked effect. The five control mice, which were infected with the streptococci in the same way but received no sulphanilamide, were all dead within forty-eight hours, while all the six which had received the drug were still alive. The work was soon confirmed, and today sulphanilamide is one of the most-used drugs for streptococcal infections. It owes it use to Domagk, for without his discovery of prontosil it would not have been tried; but the action of sulphanilamide shows that he himself worked on a false (though very fruitful) clue when he made his discoveries.

Again and again in working towards practical ends one falls back on pure science for support. The French workers did not have to discover how to make sulphanilamide: there was the method, ready and waiting for them. Sulphanilamide was discovered in Vienna by a man who was making a general study of the sulphonamides of sulphanilic acid. That man was Gelmo, and the year 1908[51]. Tucked away in the middle of his paper is a paragraph on sulphanilamide. He tells very shortly how he made it and gives an account of its properties: its whiteness, solubility, reaction with alkalis, stability to acids, and melting point (the latter 3° C. wrong, as we now know[5]). That little paragraph is one of the most tantalizing objects the world has ever known. Neither Gelmo not anyone else had the faintest idea that sulphanilamide would become one of the world's greatest life-savers. Twenty-seven years had to pass before it was discovered

that it was a chemotherapeutic agent of the foremost rank. Taylor[127] calculates that if its properties had been known, it could have saved 750,000 lives in the last war alone, from its effects on the streptococcus of septic wounds and blood-poisoning. It was just because chemists did not short-sightedly confine their attention to substances thought likely to be useful in a material way, that sulphanilamide was lying ready for instant trial directly some one had reason to believe it might serve humanity in a practical way.

It was Pasteur who spoke of the function of chance in science while he was yet a young man, and it was fitting that he himself should derive such a signal benefit from it many years later. After he had worked for some time at chicken cholera, his experiments had to be interrupted for several weeks. That interruption, unplanned, was amazingly fertile in results. When he started work again, he reverted to his old cultures of the bacilli which cause the disease and tried to inoculate them into fresh fowls[72]. The fowls did not appear to be affected, and it looked as though the cultures were useless. Pasteur intended to throw them away and start again, when it occurred to him to inoculate the same unaffected fowls with a fresh and deadly culture of the bacilli responsible for the disease. The fresh culture proved deadly enough with ordinary fowls, but most of those which had previously been inoculated from the old culture withstood the disease. During the accidental interruption of Pasteur's work, something had been happening in the ageing cultures. The capacity to produce disease was becoming attenuated, but the capacity to give immunity was retained. Pasteur proceeded to extend his great discovery to the prevention of anthrax in sheep and cattle, with a success that astonished the world.

The combination of a good scientist and good luck brings good results. It often happens that a single scientist has very

good and very bad luck, and by his success and failure shows the large element that chance must always play in scientific investigation. Mendel provides a perfect example. He chose peas for his experiments on inheritance. The choice was very fortunate, for the results were clear-cut, and he was able to lay the foundations of the branch of biology that bears his name. He also studied inheritance in hawkweeds (*Hieracium*), and devoted a lot of time to it; but he could scarcely have had worse luck than to choose this genus, and to be urged on by Nägeli to persevere with it[80a]. Nearly twenty years after his death it was discovered that in the genus *Hieracium* the seeds are often formed without fertilization, and the progeny therefore resemble the seed-parent without any influence from the pollen of another plant. A more unsuitable genus for the study of biparental inheritance can therefore hardly be conceived, though Mendel did not and could not know the reason why. He hoped that the laws he formulated as a result of his study of the pea were universally valid, and so indeed they are in ordinary biparental species of both plants and animals. Mendel naturally thought his hawkweeds biparental. He was wrong, and it was very bad luck, since uniparental reproduction is rare. If Mendel had worked only with hawkweeds, he would have been a potential but not a recognized genius.

Discoveries that benefit mankind in a practical way are produced liberally by a free science, expanding always in whatever direction expansion is possible. Constrain science within the strait-jacket of close attention to material needs, and it cannot breathe freely enough to serve mankind either culturally or practically. H. G. Wells has realized the futility of research planned *ad hoc* towards stated ends. He tells how under certain circumstances he might have become a very wealthy man. He deplores the possibility that he might

even have "endowed and dominated futile *ad hoc* research"[141a]. It is encouraging to know that such an influential man realizes that planned research is futile. The fact should be more widely known. If one's friend has an inoperable cancer, he is treated with radium or X-rays[1]. It is relevant to remember that radium was discovered by a man and his wife who were interested in radioactivity, and that knowledge of X-rays grew from the studies of those who concerned themselves with the phenomena of electrical discharge *in vacuo*. It may be anticipated that when another great discovery comes to bring help to sufferers from this disease it is likely to come from an equally unexpected quarter. Those who wish to make it come quickly cannot know how to act, but the best suggestion one can offer is the endowment of free research in various sciences. Cancer can only be completely conquered when the basic sciences have progressed far enough for full understanding. To pour out money on clinical medicine while leaving free research in the underlying sciences less well endowed is a short-sighted policy.

The active investigator should not be required continually to justify his work before others. Most good research workers try a certain number of long shots—rather crazy-sounding experiments which they do not like to admit even to their friends. Darwin, who tried them freely, called them "fool's experiments"; Bateson, "fanciful follies". Nothing exemplifies better than these the lack of understanding of the minds of research workers shown by those who demand rigid planning in advance. Bateson notices a kitchen mincing-machine for the first time. He is at once struck with the possibility of turning the instrument to scientific use. He orders conifer seedlings from a nurseryman, and immediately a fanciful folly is in full swing: the handle is rotated and the plants passed through to surrender their resins[14]

This was the man whom Haldane has called "the greatest geneticist whom England has so far produced"[58]. He did not sit down and draw out elaborate plans to look imposing before a committee of planners: he tried his fanciful follies when he wanted to do so. Sometimes such experiments succeed, sometimes they fail. It is a matter of luck. If they fail and teach nothing, the research worker should not be required to account for their failure to anyone else.

It is sometimes argued that if chance has played such a large part in discovery in the past, we should do well now to exclude it by planning for every possible contingency, so that ordered advance may take the place of unexpected discovery. The answer is that chance alone never makes discoveries. It is the combination of chance with the prepared mind. Chance we cannot plan for: the prepared mind we can select. If we choose for our research workers only those who will follow some one else's plan with docility, science will stagnate. The facts cannot be put better than in the words of Dr. J. I. O. Masson, Vice-Chancellor of the University of Sheffield. "In time of peace to insist, as various people have tried to do of late years, that the active curiosities of original minds shall be turned aside to topics selected by non-practitioners or lay-arbiters as bearing on current public problems; to constrain into 'practical' themes men of highly specific abilities, whose reason for living hard and (by newspaper standards) inconspicuous lives is that they crave to know certain sorts of unknown things and can endure the long process of finding out: all this is a kind of regimentation which would frustrate its own ends. For the mind of the genuine researcher (as distinct from imitations, here negligible) simply will not work productively upon things in which it is not technically interested, or on 'problems of the day' which he knows are too crowded with shifting and arbitrary variables to be resolved by means of his

specific aptitudes. Each researcher is a key that opens only the range of locks which it fits. His own results are normally what the public calls 'useless', because they are beyond the horizon of even the educated contemporary layman, and because the integrated effects of them and their like will not reach the surface of public apprehension for a long time to come"[93].

Let us have one plan only: the plan to choose as our investigators those active, independent, untamed people who, by a combination of alert and prepared minds, intense enthusiasm, luck, fools' experiments, and more ordered schemes of their own, are capable of making real discoveries. Such people will be ready for the arrival of an idea at any time of day or night. Naturally they will devise a method of research. They will be better equipped than any scientific dictator or planning committee to see how their own particular aptitudes can be put to the task of expanding the bounds of knowledge. Working along a line devised by themselves, they will be ready and free instantaneously to switch their energies in a new direction, if the unexpected appears. Good men are what science will always thrive on, not dry, dictated plans.

Chapter 6

The Origin and Nature of Science

"The greatest truths are perhaps those which being simple in themselves illuminate a large and complex body of knowledge."
ALEXANDER[3]

The University of Chicago. A time and motion comparison on four methods of dishwashing : a dissertation submitted to the graduate faculty in candidacy for the degree of master of arts. [80]

Curiosity

So far as their sense-organs will allow, animals apprehend truly those attributes of objects and phenomena of which they take cognizance. Truth has selection-value. An animal could not survive which was personally insensitive to truth, and went in one direction when the evidence of its senses suggested that it would find its food in another. This perception of truth is not limited to what immediately concerns it: an animal is aware of objects in its environment which have neither positive nor negative value for it. When, in the evolution of human beings, the power of speech began to be developed, primitive man maintained his animal ancestor's apprehension of truth. He was unpractised in verbal deception, and it is only reasonable to suppose that when he conveyed information to another person by the first rude attempts at speech, he conveyed, so far as he could, the truth. Thus was made possible, many thousands of years later, the birth of science. If the sense-organs of

animals and early man had evolved in such a way that only useful and harmful objects could be apprehended, science could never have been born.

To say that truth has selection value is of course not the same thing as postulating that any thought, originating from sense-perceptions of the environment and having selection value, is necessarily true. As Mr. R. Brown has pointed out to me, the beliefs of various Eastern peoples about pork have selection value, though they are false. Selection value provides no criterion of truth; but no such thing as appreciation of truth could have arisen if truth did not possess selection value far more usually than falsity.

Evidence is beginning to be collected showing that the lower animals recognize objects by tests which are different from those we apply to the same objects, but there is no reason to suppose that our remote half-human ancestors in Pliocene times differed materially from ourselves in this respect, for the sense-organs and the parts of the sub-human brain concerned with perception must have been fundamentally the same. Early man, it must be inferred, saw roughly as we see: and within him was the urge to see more widely. This point has perhaps been insufficiently stressed. Before he could get about otherwise than on his own legs he had already spread over nearly the whole of the habitable surface of the globe, though he could not fly like a bird or even gallop like a horse. This world-wide distribution of a single species of a heavy terrestrial animal is unique, and the mere necessity to look for food and shelter is unlikely to have been a sufficient stimulus to have caused early man to walk voluntarily into the barren and inhospitable areas which he occupied. He was inquisitive about the environment as a whole, as many animals are. One has only to watch a cat investigating an unfamiliar object in her haunts to see an embryonic rudiment of

a curiosity resembling man's. J. G. Crowther[26] says that curiosity is a sublimation of the desire for power, but somehow it is strange to think of fishes indulging in sublimation, yet fishes show curiosity[117]. The Primates go infinitely farther than fish or cat. Darwin saw a monkey investigating a lens and succeeding in placing it at the proper distance from its eye to obtain a focus[37]. Everyone knows how inquisitive monkeys are; the fact is inescapable, and no light is thrown on the subject by saying that they are only sublimating power-urges. We live today because our ancestors were inquisitive and went—because they wanted to go—outside their haunts to find unfamiliar objects and investigate them. St. Augustine condemned the "vain and curious desire of investigation", but he would not have lived if his ancestors had not possessed it.

The investigation of objects carries with it the necessity to generalize about them, and it is inescapable that the capacity to generalize must have had a selection-value, for an individual which regarded each object as *sui generis* would be at a disadvantage in the struggle for existence against others who could infer the properties of objects from their resemblance to those already known. The necessity to generalize may have appeared subjectively to early man, as it does to us, in the form of pleasure in finding order. Pleasure in curiosity and in the satisfaction of curiosity combined with pleasure in generalization were the rudiments from which has grown that part of science which may be called "natural history" (see p. 92). Curiosity by itself is of course not a mainspring of science. Completely unscientific people are often very curious about all sorts of matters which cannot be welded by generalizations into an ordered system of demonstrable knowledge.

Every instinctive feeling varies in its intensity in different people. In conformity with what is known of inheritance,

one must suppose that the variations in intensity are governed partly by inborn factors and partly by the environmental conditions, especially of youth. It would be strange indeed if everyone had identically the same desire to enquire and to generalize about the results of enquiry, and in fact one finds the whole gamut of variation in present-day life from the man whose pre-occupation is the football-pool to the greatest minds of modern science. No one can tell whether heredity or early environment generally plays the larger part in the production of a scientist: however favourable the inheritance, extreme unsuitability of early environment will crush it unless one has the innate ability of a Faraday or a Mendel, while if the innate desire to find out and generalize is conspicuously small, no amount of encouragement or provision of lavish facilities will avail.

Although curiosity and the desire to generalize are characteristics of the scientific mind, yet clearly they cannot alone create a scientist: originality and intelligence and perseverance are necessities, and the finding of pleasure in the use of the hands in delicate manipulations is very nearly necessary. The presence of this combination of qualities in a higher degree of development necessarily differentiates the natural scientific investigator from those in whom they are relatively deficient.

Observation and experiment

The demonstrable facts, whose observation, recording and grouping constitute the province of science, present themselves to the observer in two different ways: they may be either explicit or implicit. My choice of the word explicit does not indicate that the study of this group of facts is easier than that of the other, but only that they are ready for observation without the necessity for the observer to produce artificially the conditions under which they will

arise. The explicit facts require observation only, the implicit ones require experiment. Some explicit facts, such as the minutest striations on the shells of the microscopic plants called Diatoms, are very difficult to observe; some implicit ones, like the regeneration of a flatworm when a part is cut off, are very easy.

The only difference between explicit and implicit facts lies in the circumstance of whether the observer interferes with the subject of his study in such a way as deliberately to change it artificially; it depends on whether the human will has operated to change the object observed. When the observer mounts Diatoms in special media to make their striations more apparent and uses a microscope to view them, he is only taking steps to observe explicit facts. The use of reagents and instruments does not make his method experimental. If, however, he were to crush the Diatom to study the nature of the fracture of the shell, he would be studying implicit facts or making an experiment. It is not easy to understand but it is nevertheless true that some scientists are more attracted by the study of explicit and others by that of implicit facts, though there is no essential difference between the two kinds. It is in biology that the two kinds of facts give the strongest impression of being really different. The organism is either studied as it appears in an ordinary environment, or else in an environment which produces changes in structure or function which would not have originated apart from the operation of man's will. These changes are fascinating to some minds, while to others they are much less interesting than the explicit facts of the structure and behaviour of the organism in its "natural" state.

There is no intrinsic value which would place observational above experimental methods or *vice versa*. Some parts of science require one method and some another: many

require both. The notion that science is served only by experiment is fallacious. Waddington[139] says that "science is concerned to discover how things work, and its test of truth is that it can make them work as it wants to". Thus the whole heritage and future of observational science—astronomy, for instance, and palaeontology—is discarded, and all the emphasis is placed on experiment and human "want".

The experimental method is, of course, an essential part of many branches of science. Modern botanists would be horrified to read an old-fashioned statement that botany is an observational science. The great American biologist Morgan has well suggested[104] that it would be as absurd for biologists to rely wholly on observation as for physicists and chemists to confine their activities to the study of such natural phenomena as thunderstorms and volcanic eruptions. This must be readily allowed, yet such a thing as observational science is necessary, and at the end of this chapter I shall suggest that it may be helpful to classify the largely observational sciences together as "natural history". I once knew a man who used to say, in answer to non-scientific strangers who asked what his job was, that he was an experimental biologist. He enjoyed their bewilderment. I confess that I was as bewildered as the strangers, for a man might as well deliberately make scientific research more difficult for himself by cutting off one of his hands as discard purely observational methods when they will help as guides to understanding. In both observational and experimental science it is the answer to a question that is sought, not the fulfilment of an attempt to make things work as one "wants". The introduction of the word "want" into a definition of science brings to mind a question, indicative of a naïve misapprehension of what science means, which scientists may sometimes find themselves asked to answer: "What are you trying to prove?"

The definition of science

How, then, may science truly be defined? The aim of natural science, as Findlay[47] has said, "is to acquire as complete a knowledge as possible of the material universe; of the objects, materials and phenomena and the relations between the phenomena which make themselves known to us or which we apprehend by means of our senses". By following this finely-stated aim a structure of knowledge is built up which, as A. V. Hill[66] remarks, "is approved by all sane men"; though it would be wise to add that only the sane men who have studied it are in a position to give their approval. Approval is actually an understatement of the feelings of men towards that "body of valid ideas"[110] which constitute science. Polanyi, in his great though short statement of the true significance of science, has remarked how nothing has proved so permanent as the systems of science. "Waves of civilization have come and gone over Mesopotamia, Egypt, and Europe, and while their creeds and laws, and often even their crafts, may have been forgotten, their contributions to systematic science have been preserved. It seems that an ordered framework of ideas in which each single part is borne out by the cohesion of the whole is of supreme attraction to the human mind. Struggling for a foothold in a shifting world, the mind clings persistently to these rare structures of sound and consistent ideas. It is in these structures, accordingly, that all scientific interest resides"[110].

Whether we speak austerely, with Hill, of "approval", or enthusiastically, with Polanyi, of "supreme attraction", we mean the same thing: science has a human value as an end in itself.

Science, as Alexander has said, is not "a mere repetition of facts; that would be chronicle and not science"[3]. A discovery is "important" in science when it illuminates a large

field of knowledge: the larger the field it illuminates, the more important it is. Often the great discovery is attractively simple. "The birth of the greatest truths is for the most part an event in which some simple statement of the widest generality emerges out of a great mass of more or less separate pieces of knowledge to which it suddenly supplies a clue or enables it to be taken in at once in a flash"[3].

J. G. Crowther[26] has defined science as "the system of behaviour by which man acquires mastery of the environment". We should laugh if a man set out to define "army" and gave a good definition of "navy" by mistake; yet this is exactly comparable to what Crowther has done. His definition is a good one, but not of science: it is a definition of technology. It is important that no energy should be wasted on an argument about words, and it is therefore convenient to say that one of the contrasted subjects is called science or pure science or fundamental science, and the other is called technology or applied science or (by those who distinguish between the two latter) technology and applied science. I do not mind at all which of these words or phrases is used, but in this book I generally use simply "science" and "technology". Technology serves man's material needs directly, and his spiritual needs indirectly (by providing, e.g., the ink and paper used by writers and composers). The uses of science are discussed in the next chapter. Here it must suffice to say that its principal uses are two: to serve as an end in itself, like music, and to form a basis for technology.

Just as the concepts "boy" and "man" are useful and generally valid, so are the concepts science and technology, despite the fact that the distinction cannot always be made with precision. There are, however, various guides on which some reliance may be placed in doubtful cases.

Science is essentially inductive. Facts are collected so that generalizations may be drawn from them. Technology,

on the contrary, may almost be called deductive: use is made of the generalizations of science to deduce how material human wants may be satisfied. Those working deliberately towards material human welfare often make discoveries which are of scientific value: in so far as they do that, their work is not technological. Pharmacological research provides an example. There is much that is not scientific about our knowledge of the action of drugs, but when the facts compel a generalization, the subject is as scientific as any other. For instance, the knowledge that certain drugs stimulate the endings of the sympathetic nervous system and others those of the parasympathetic system is a part of science. It remains valid and interesting whether such drugs are used in pharmacy a hundred years hence or not.

That brings us directly to a second test of distinction. In science, every discovery is of permanent value, and serves as a basis for other discoveries. In technology discoveries are often of ephemeral value. When gramophones are invented, the musical box becomes less interesting. No fact discovered by technologists can be untrue, but its interest can wax and wane exceedingly in response to human needs and even whims. The test of the importance of a technological discovery is service to potentially-ephemeral human needs; the test of importance of a scientific discovery, as we have seen, is its capacity to link up and illuminate other facts, and that can never change.

Technology is deliberately eclectic, while science aims always towards completeness. If science disappeared and only technology remained, knowledge would be a hotchpotch instead of an ordered system. Special investigations would continually have to be made to find out basic facts which would have been common property long before, if science had survived.

The indulgent reader may allow a little parable which

serves to distinguish science from technology in a way that will in some cases be found helpful. Suppose that a terrible disease ravaged mankind and human beings became extinct. Suppose that the mind of another animal evolved until it equalled that of man. Imagine that this happened, for instance, to the hippopotamus. (If the reader is inclined to smile, let him ask himself whether a visitor from Mars would find the grant of intelligence to a hippopotamus or to an ape the funnier.) Eventually the hippopotami would build up a science, even though difficulties in manipulation of apparatus would make progress rather slow. Atoms and molecules would be discovered; the structure of the benzene ring, even electrons and quanta would at last be disclosed. Meanwhile the hippopotami would be constructing special mechanical carriages for their more convenient and rapid transport from place to place, and discovering drugs to alleviate the ills to which their flesh was heir. Let us now look at the sum-total of their knowledge. Their engineering and pharmacy would be quite different from ours: their chemistry and physics, on the contrary, the same. Chemistry and physics are sciences, engineering and pharmacy are technology.

It would take us too far to pursue these imaginary events in detail, but this may be noted. If the hippopotami discovered generalizations about the actions of drugs on the sympathetic and parasympathetic nerve-endings, these, as we have seen, would be science; but their study of social hippopotamology could only be regarded as unquestionably scientific if it were related to knowledge of the social life of other animals.

Technology, of course, itself brings advantages to science. I never cease to be genuinely thankful to the engineers whose work has made light, heat and water available in my laboratory at the touch of a switch or tap. These

conveniences are as useful to me as typewriters and printing-presses to writers. They are invaluable, although they provide no inspiration.

Nothing in this book is intended as an attempt to minimize the magnificent achievements of technology. Such a stupid attempt would in any event be futile. I have myself worked for years in both technological and scientific research. I know the radical differences of atmosphere and approach in the two subjects and the special attractions and difficulties of each. To myself science makes the greater appeal. This is a personal, subjective matter. Edison and Marconi may be cited as very great technologists, Faraday and Darwin as very great scientists. It is wise to refrain from arguments as to which is the higher form of activity. The energy spent on such an arid discussion would be better used in seeking to find the right places in research for the right people, according to whether their personal inclinations are towards science or technology.

Technology should not be magnified at the expense of science. In recent years the British Association has shown a definite tendency in this direction, and has laid itself open to the charge of having become an Association for the Advancement of Technology. Such an association might be an admirable one, but it should not arise at the expense of science. Anyone who magnifies technology at the expense of science is like a man who cuts down a tree because he is so anxious to get the fruit that he forgets the necessity for roots and stem and the potential beauty of next year's flowers. Science is a perennial; the roots and stem must be allowed to survive, and the ground be cultivated, so that flowers and fruit may come again another year.

Logic and mathematics cannot, I think, be included as component parts of science, despite the important contributions they make to certain aspects of scientific work. It is

a striking fact that persons untrained even in the elements of logic are usually logical enough for all the purposes of ordinary scientific research, though it would be far from my intention to belittle the subject, which Herbert Spencer regarded as forming, with mathematics, the abstract division of science[122]. It seems desirable, however, to separate mathematics and logic more sharply than this from that study—science in the narrower sense—which is concerned with information received through the sense-organs. If a person blind from birth and lacking the sense of touch were sufficiently intelligent and could picture to himself such imaginable things as separate objects and such unimaginable ones as points and lines, he could dictate the whole of mathematics (except perhaps probability) out of his head without any instruction or the necessity to know anything about the universe. Logic and mathematics, as Driesch[40] says, constitute the "realm of mere meanings", which he separates from "the realm of Nature", which is equivalent to science. The mathematician, the same author remarks, investigates "*the* sphere"; the scientist investigates "this *one definite sphere*" (which, it might be commented, is never spherical).

The argument as to whether mathematics is a part of science is, of course, largely an argument about words. The use of sensory perception in the one study, and not in the other, is probably sufficient justification for the adoption of a single word to cover all branches of the former study, even though the process of generalization is shared with the other and has indeed been carried much further in it. The only single word which has been used to mean the recording of sensory perceptions of the universe and generalization about them is *science*, and it may be suggested that the wider meaning sometimes attached to this word has on the whole more disadvantages than advantages.

A classification of the sciences

Any classification of the sciences must be arbitrary and convenient rather than demonstrably true, but I want tentatively to suggest that it may be helpful to classify them in four groups: basic, intermediate, expanded and eclectic.

The basic sciences are physics (including mechanics), chemistry, astronomy, geology and biology. Each of these is of course divided into basic sub-sciences: thus the study of geographical distribution is a sub-science of biology. Biochemistry is an obvious example of an intermediate science. It is difficult to decide whether such sciences are genuinely intermediate, or whether they have only obtained their intermediate position because science has chanced to develop in a particular way. The fertilizing contact of people trained in different schools of thought has probably been responsible for the rapid growth and extraordinary interest of intermediate sciences, when at last people begin to bridge the gulfs. Anthropology and psychology are expanded sciences: that is, they constitute parts of the basic science of biology, but they have necessarily been so greatly expanded by the peculiar status of man and mind in the universe as to deserve separate recognition. Pharmacology, pathology, physical geography and meteorology may be regarded as eclectic sciences, not simply intermediate between certain of the basic sciences, but drawing upon chosen parts of two or more in such a way as to illuminate special fields of investigation.

Pharmacology is a very special kind of science. It could be set apart as technological if the inductive method had not been used in it with such success. It is very exceptional in the sharp limitation of its field. A worker in any other science cannot fail to be surprised when he reads about drugs of plant origin in book after book of pharmacology and notices

no mention of the significance of those substances in the lives of the plants themselves. Such a deliberate limitation of interest is as surprising as the fact that scarcely a single valuable plant drug was first tried on the recommendation of a pharmacologist: nearly all were first used by simple, uneducated people. The inquisitiveness and initiative of the nameless discoverers are truly remarkable and would scarcely be thinkable in present-day Europe, where discovery is unfortunately left by common consent almost entirely to professional laboratory workers.

Rather a sharp cleavage between two kinds of outlook divides the biologist from the non-biological scientist. The cleavage is caused by the appearance of purposiveness in living organisms. An example will illustrate the point. Haemoglobin, the red colouring matter of the blood of man and many animals, is readily oxygenated and the oxygenated compound parts readily with oxygen. This fact is regarded by biologists as very important, because it is made use of by so many animals for the transport of oxygen to the tissues. Haemoglobin has, however, another very curious property. It can act as what is called a "peroxidase": that is, it can decompose hydrogen peroxide with the production of active oxygen. This is something which apparently never happens in the blood of living organisms. Biologists therefore regard this property of haemoglobin as much less interesting than the other, although both equally are properties of a substance which is only formed in living organisms and which therefore belongs to their realm of investigation. Chemists and physicists look on facts and phenomena in quite a different way. They are just as interested in reactions which never occur in natural circumstancs as in those which are occurring all the time (e.g., in volcanoes). The biologist is interested in the organism as a going concern. He regards those attributes of its component parts and substances which

do not affect its survival and reproduction as far less important than those that do.

Natural history

There exist criteria, rather convenient for some purposes, by which the whole of science may be cut right across and separated into only two divisions. Of these one may be called general analytical science and the other natural history. The latter is a valuable phrase, though it has been used in different senses. In common speech it is sometimes used rather loosely to mean those parts of biology which can be pursued without special training or the use of special instruments. Karl Pearson[108] has used it in an extraordinary way, which I shall not adopt: for him, natural history is not a part of biology or vice versa, but is contrasted with it as a separate part of organic science. This use of the phrase presents no advantage and has no historical basis. Thomas Hobbes[67] defined natural history as "the history of such facts or effects of nature as have no dependence on man's will; such as are the histories of metals, plants, animals, regions, and the like". He contrasted this with civil history, the history of the voluntary actions of man. Everything in modern science except psychology and social anthropology would be included in his definition of natural history. The great French zoologist, Baron Cuvier, narrowed the definition considerably. He divided all science into "physique générale" and "physique particulière"[27]. The former comprised what we now call physics and chemistry, and Cuvier defined this part of science as that in which bodies may be isolated and reduced to their utmost simplicity, and their properties brought separately into action. By particular physics he meant the study of those objects which do not allow of rigorous calculation or of precise measurement in all their parts. The phenomena here occur under circum-

stances which do not permit an experimenter to reduce the problem to its elements: it must be taken whole, as, for example, when one examines the activities of a whole living organism.

Cuvier used the words "l'histoire naturelle" as synonymous with particular physics, and stressed the relative importance of observation in this sphere in comparison with experiment. He thought it best to range astronomy and meteorology with general physics. For him, then, natural history may be taken to mean botany, zoology, and geology; but he would presumably not have included present-day physiology, in which analytical methods and experiment play so large a part.

There is an element in Hobbes's definition which is helpful to the concept of natural history. Man's deliberate will is such an extraordinary phenomenon in the universe that attention may properly be paid to it in a classification of the sciences. Though probably it cannot be separated in kind from the mental activities of the higher animals, yet it transcends them so much in degree that one may readily allow a special adjective, "natural", for objects and phenomena which are not at all or not greatly influenced by it. T. H. Huxley[77] said, "Nature is, of course, the totality of all laws", and I remember reading somewhere that the natural is simply that which occurs; but if we make the word co-extensive with everything, we extend it to the point of depriving it of meaning.

The phrase natural history, then, may be used to cover the investigation of particular explicit objects and phenomena, which can be studied as wholes mainly by observation without much or any human interference; e.g., a thunderstorm, or the movement of the moon, or the normal growth or habits of an animal. General analytical science, on the contrary, is concerned with general rather than particular,

and implicit rather than explicit facts; it usually requires human interference by means of experiment. Examples are the study of the chemical properties of an element or of the behaviour of gases under various pressures and temperatures.

In this broad grouping of the sciences, we may classify under the heading of natural history a large part of biology together with geology, meteorology and astronomy. The latter two subjects are so much concerned with particular rainfalls and particular stars that I cannot follow Cuvier in excluding them from natural history. (Cuvier himself felt doubts about these two subjects, especially astronomy.) Physics and chemistry are the general analytical sciences *par excellence*. The extent of the use of experiment and analysis in genetics and physiology bring these biological subjects within the group of analytical sciences. The tendency in animal physiology is to disregard the activities of the organism as a whole, and to study it without careful consideration of its relationship to other animals, its evolution, its geographical distribution or its natural habitat and habits.

It would be far from my intention to suggest that experiment is not used in biology except in genetics and physiology, or that observation without experiment is not used in physics; but I think that most scientists may be grouped according to whether their main inclinations are to general analytical science or to natural history. It is rather because I believe that there are two main kinds of scientists, than because there are necessarily two main kinds of science, that the division of science in two is suggested. Those who may be called the natural historians derive their impetus to research, I believe, directly from their ancestors' interest in the environment, with which subject the first part of this chapter is concerned. The interest exists in everybody;

when it is very strong, the person tends to become a research worker in one of the natural history sciences or an explorer in the geographical sense. The analytically-minded person, who finds little interest in wholes and tends to be interested in substance rather than form, in the general rather than the particular, in the implicit rather than the explicit, is more difficult to account for on an evolutionary hypothesis. While we see the exhibition of curiosity about the natural environment in a wide range of animals, deliberate interference with nature for the purpose of gaining knowledge is almost confined to man, and probably evolved as the capacity to use tools was being perfected. Elements of this kind of mental make-up exist in everybody, but those in whom it is particularly strongly developed tend to become research workers in physics or chemistry. Although interest in the environment and in its alteration by tools were both useful to primitive man, yet their direct usefulness brought man as short a distance on the way to scientific culture as the love-cries of the ancestral ape have brought him in music (though it must be admitted that not everyone can sing an octave in semitones as accurately as certain anthropoid apes[35]). There is no evidence that the potential brain-power of man has evolved during the historical period, nor any knowledge which would suggest that such evolution could have occurred. By the use of tradition, first oral and then by writing and finally by printing, inquisitive and analytical minds have passed on, from generation to generation, the fruits of their studies, and thus knowledge has been built up to the magnificent heritage of present-day science. The stimuli have been primitive urges which were useful to prehistoric man, scientists have used those urges differently from their remote ancestors. Just as speech no doubt evolved on account of its practical usefulness, but has given us our heritage of literature, so science has transformed itself in such a way

that the greatest discoveries have not been made in response to material need. If each generation of man had always to start where the last generation started, the primitive urges would get him no further than the fulfilment of immediate material needs and increase in the range of his species. It is through step-like progress, made possible by each generation possessing at the start the treasures of the one before, that man has been able to transcend the functions of his primitive urges and produce modern culture.

Neither general analytical science nor natural history is superior to the other. Scientists should be ready, as we have seen, to use observation or experiment or both according to the nature of the problem in hand, and not to tie themselves down as to the particular method of approach. There is some tendency for general analytical science to be given a higher standing than natural history. Indeed, as my friend Mr. Charles Elton remarked to me long ago, one can arrange some of the sciences in an order (physics, chemistry, biology, anthropology, psychology) in which the exponents of each tend to regard themselves as superior to those of the next. More remarkable still is the fact that scientists in all groups except physics (which has no "superior") tend to look with a certain amount of awe on the sciences before them on the list. These ideas are crystallized in the statement, attributed to Rutherford, that science consists of physics and stamp-collecting. This is an epigram intended to mean that particular objects are uninteresting: it is the extreme view-point of a general analytical scientist. It is true that chemistry rests partly on physics, biology on chemistry, and anthropology on biology, and that psychology must eventually rest on anthropology and biology; but this in no way invalidates demonstrable facts in any science. A good classification of a group of animals is valid although we cannot yet describe the chemical differences in the genes which make one

animal different from another. Psychology has produced valid concepts which cannot yet be linked up with brain physiology. True science never arbitrarily limits itself, and psychologists and brain physiologists will no doubt work gradually towards each other's spheres; but it is neither necessary nor desirable to wait until a gulf is bridged, before cultivating the land on the other side. Science would be very poor in total content if we dismissed everything that cannot be stated in terms of electrons, protons and quanta. Feelings of superiority and inferiority do nothing for the welfare of science and should be forgotten. Each research worker should take his place in that sphere in which he feels that he can make the greatest contributions to knowledge.

Chapter 7

The Uses of Science

". . . until a sufficient foundation of pure science has been successfully laid there can be no applied science. Real progress comes from the pursuit of knowledge for its own sake."

TILDEN[132]

SCIENCE, as was pointed out in the last chapter, has two principal functions. It exists as an end in itself, finding its natural place in culture alongside music, art, literature and philosophy. It exists also as the only possible base from which technology can advance. These two functions are both useful.

There has been much misunderstanding about the word "useful". People have often restricted the sense of the word to make it synonymous with "beneficial in a material way", and some have even further confused the subject by using the word "utilitarian" with the same meaning. Since utilitarianism is intimately connected with the philosophy of J. S. Mill, it greatly simplifies argument if the words are used as he used them.

Mill[99] made it clear that whatever increases pleasure or decreases pain in any sentient creature is useful or utilitarian. He maintained that usefulness has no other meaning. He found it impossible to oppose the agreeable or ornamental to the useful. He allowed, naturally, that some kinds of pleasure are more desirable than others. There is a sense of dignity possessed to some extent by all human beings, which leads them to prefer one kind of pleasure to another.

It is particularly the kind of pleasure which man does not share with animals that men regard as the highest in quality, so that they consider it "better to be a human being dissatisfied than a pig satisfied". As Mill said, no intelligent person would willingly consent to be a fool, even if he were fully persuaded that the fool is better satisfied with his lot than he is himself. People who have experienced pleasures which employ their higher faculties give a marked preference to these over the lower pleasures, such as that of eating.

When anyone is undernourished or lacks sleep or shelter or warmth or health, nothing is more useful to that person than the provision of material help; but when everything has been rectified, there remains a void unless something can exist for that person as an end in itself. In the modern world people fight shy of the concept of the end-in-itself with a scarcely comprehensible evasiveness. In art they will even pretend that beauty is solely functional, though everyone who has a garden and grows flowers without making material use of them (e.g., for pharmacy) is a silent witness that the appreciation of beauty is in fact an end in itself; for not one gardener in a hundred is interested in the function of flowers, which is the achievement of cross-fertilization. Those who say that nothing except suitability for material ends gives beauty will also find themselves in difficulty over music, for apart from its outstanding performance at the siege of Jericho, it has seldom been of material service to man except as a means of keeping soldiers in step and stimulating their martial ardour.

Those who appreciate science as an end in itself are subjectively aware of its value to themselves: it is to them what music is to the musical. In Chapter 9 a plea is made for the wider spread of scientific culture, so that the greatest possible number of people may benefit from it as an end in itself. This aspect of science has not been sufficiently recognized.

Scientists would be selfish people if they wished to keep the culture of science within closed walls: indeed, if they succeeded, the subject would scarcely deserve to rank as culture. Not every scientist could or should be himself a disseminator of scientific culture, but in Chapter 9 ways will be suggested in which that culture could be spread so as to give the maximum benefit to humanity.

Galen, nearly eighteen centuries ago, recognized the importance of knowledge of anatomy not only for the physician but also, as he said, for the philosopher[129]. That was his way of acknowledging its value as a final end. This acknowledgment springs from subjective and not objective experience and cannot therefore become a public truth. If a man says, "I appreciate the music of Beethoven apart from the possibility of its use for keeping soldiers in step", we cannot by any objective means prove him truthful or a liar. It is the same with science: no satisfying proof is possible. The fact remains that the individual scientist knows certainly what a tremendous value science has for himself as a final end, and he infers from the disinterested enthusiasm of his colleagues that it appears in the same sort of light to them.

One knows that scientists are absorbed in science as composers and artists are in music and art. J. A. Crowther (who must not be confused with J. G. Crowther) has written[25], "In spite of the difference in their working media, the man of science, philosopher, poet, and artist belong to the same category; as anyone who has had the privilege of working under any of the great men of science of the age can easily realize." Even when Perkin had discovered aniline dyes (see p. 64) and was exploiting them commercially, his heart remained devoted to science for science's sake[133]. He always continued research in science apart from his technological work, and in the end reverted to it entirely. That is the usual

attitude among those scientists who make great contributions to material human welfare. In his speech at the opening of the Faculté des Sciences at Lille, Pasteur told his audience that it would not be their part to "share the opinion of those narrow minds which scorn everything in the sciences which has not an immediate application"[136]. Nearly ninety years have gone by since Pasteur spoke those words, but narrow minds are still with us, and indeed they are much more influential in our time than they were in his.

The first of the five propositions to which the members of the Society for Freedom in Science adhere is this: "The increase of knowledge by scientific research of all kinds and the maintenance and spread of scientific culture have an independent and primary human value." This sentence expresses so exactly the feelings which are known to animate most scientists, that it would be unnecessary to labour the point if certain thinkers had not adopted rather an equivocal position which demands careful consideration. Although their thesis contains valuable elements, yet it can serve to confuse the issue.

Bertrand Russell[118] is the chief expositor of a function for science intermediate between its service as an end in itself and direct application to material ends. It would appear that he does not himself accept the function of science as a final end. "Perhaps the most important advantage of 'useless' knowledge", he says, "is that it promotes a contemplative habit of mind." Immediately one asks, "So that one can contemplate what?" If science is the answer, then science is allowed to be an end in itself. But apparently this is a short-circuit not intended by Russell, for he says that mental cultivation "gives other interests than the ill-treatment of neighbours, and other sources of self-respect than the assertion of domination". This is very true and valuable, but it seems that he is not regarding science as an end in

itself, but only as a means of preventing quarrels. He also regards science as a means of preventing unhappiness in general, which it certainly can be, though this is a curiously negative and partial exposition of the possibilities of scientific culture. "A life confined to what is personal is likely, sooner or later, to become unbearably painful; it is only by windows into a larger and less fretful cosmos that the more tragic parts of life become endurable." These thoughtful and helpful words actually tend to obscure the positive concept of science as an end in itself. Raymond Mortimer has written in much the same vein about the appreciation of nature, though he was not thinking specifically of its scientific appreciation[105]. Mill himself came near to the same position when he wrote, "Next to selfishness, the principal cause which makes life unsatisfactory is want of mental cultivation"[99]. Hopkins stresses a positive value in science which may be associated with Russell's rather negative but valuable one. He points out[73] the debt that is owed to Darwin, Lyell and T. H. Huxley for their work in spreading a belief in the value of intellectual honesty.

It may be concluded that art, music and science have a first function as ends in themselves and a second one in making the mind less petty and more honest, and thus helping in problems not connected with the subjects themselves, e.g., by giving consolation in unhappiness. Beyond these two functions science has the third and very important one of forming a basis for technology. Art also has this function, in so far as it affects the design of materially useful objects, unless its effect upon design be regarded simply as an aspect of the first function. Music cannot claim to share the third function, since the only techniques which it affects are the internal ones of the manufacture of musical instruments and the acoustic design of auditoria. Science could not claim to share the third function, if it only provided

a basis for the technique of manufacturing scientific instruments.

It would be futile to try to assess the values of the different functions of science. It must be admitted that nothing at all can be more stultifying to a discoverer than to have to think continually about whether what he discovers is going to be materially useful. Similarly there is absolutely no point in trying artificially to suggest material uses for studies whose intrinsic interest is their justification. For instance, there is an immense amount of knowledge of the extinct reptiles called Dinosaurs, and in fact it has been said that "to quote all the literature or to refer to all the Dinosaurs would require not a book but an encyclopaedia"[125]. The rise and fall of these astonishing animals is interesting to anyone. (Incidentally it may be mentioned that very good reconstructions of some of them are given in Disney's film, "Fantasia", in which they come to life in a convincing way.) Swinton's valuable book[125] on these animals is not helped but damaged by an almost pathetic attempt at the end to show that certain aspects of their study might perhaps be practically useful to the prospector or the mining engineer. This is comparable to the simile used before of keeping soldiers in step by the music of Beethoven.

It is rather curious that materially-minded people regard the first function of science as play, while a great scientist who laid the chief stress on that function used exactly the same word for the material use of knowledge. Archimedes regarded his extraordinarily ingenious mechanical inventions, for which he was famous, as merely "the diversions of geometry at play"[63], despite their real and highly appreciated material value. Knowledge apart from material uses was for him of enormously greater value. Some scientists approximate to one view-point and some to another, but no one can advance science by minimizing any of its values.

No one can say for certain that any piece of knowledge will never be of material use to man, but one can and must deny J. G. Crowther's statement[26] that "Nearly all scientific discoveries have proved of practical value". An enormous amount of discovery has been done, for instance, in connexion with the classification and geographical distribution of organisms, the migration of birds, mimicry, coral reefs, histochemical tests, experimental embryology and regeneration, that has never yet found practical application. These are only a few random instances taken from the zoological field. Some people are luckily so constituted that they will not agree to remain totally ignorant of such extraordinary phenomena as the migration of birds and the growth of coral reefs, simply because they are not convinced that the study of these problems will benefit man in a practical way.

Simple people, living close to nature, show an intense interest in natural objects and phenomena quite apart from their material use. I have found this both in the Sinhalese population of the vicinity of the Sinharaja rain-forest in South-West Ceylon and also among the savages of the New Hebrides in the Pacific Ocean. Indeed, a scientist of the kind which I have called the natural historian (see p. 92) would find himself more at home with these people than among the city-dwellers of his own country. I was once walking along a knife-edge ridge in the mountainous centre of the island of Espiritu Santo in the New Hebrides, when a conversation occurred which has stuck in my head ever since. I was two and a half days' arduous journey from the nearest white man, and my companions were the local savages and my native porters. The local people conveyed some information to me as we went southwards along the ridge. It had to be converted into pidgin-English by my porters and I shall here re-convert it into my own tongue. They were telling me that the rain which fell on my right

hand would reach the sea on the west coast of the island, while that which fell on my left would follow an entirely different course and reach it in a huge bay on the north coast. Here, extremely remote from anything resembling what most people call civilization, I was receiving a physiographical lecture on watersheds! I had had an equally striking experience many years before, when on an expedition to the Banks Islands, to the north of the New Hebrides. My companion, Mr. T. T. Barnard, found that the natives understood the extraordinary habits of cuckoos, without having received information on the subject from white men. These examples serve to show the innate tendency of human beings to take interest in the environment, without regard to material usefulness. It is shown also by the extraordinary profusion of native names for living organisms, whether materially useful or not, in both the New Hebrides and Ceylon. In both places some of the natives are relatively uninterested in natural history, others intensely interested and in possession of a considerable amount of knowledge. Neither they nor academic botanists would agree with the remark of Socrates that he "had nothing to learn from the trees". Every tree has its native name, and its correct identification is a matter of interest, to be argued about seriously if necessary.

False indeed is the idea that things can only attract the study of human beings if they are of immediate material use. J. G. Crowther states dogmatically that "science is a product of human demands". "Science has evolved", he says, "from crafts and industry." Hogben[71] has written much in the same vein, and even gone so far as to reach a *reductio ad absurdum*. "From a landsman's point of view", he writes, "the earth remained at rest till it was discovered that pendulum clocks lose time if taken to a place nearer the equator. . . . After the invention of Huyghens the earth's axial motion was a

socially necessary foundation for the colonial export of pendulum clocks." The suggestion that the only people (except sailors) who find interest in the fact that the earth revolves are those who can profit by the knowledge by making the necessary adjustments when exporting clocks towards the equator, is nothing short of fantastic. Hogben's words might have been written by an opponent who wished to satirize the opinion that science has no other function than to supply the material needs of man. The absence of a pendulum in a watch frees it from the effect of the earth's rotation, and Polanyi ironically and wittily suggests[110] that nowadays we may perhaps abandon the uninteresting idea that the earth rotates, because we mostly carry watches.

A proof that practical necessity is not required for scientific advance is provided by the many inventions of apparatus devised for purely scientific ends in the laboratory, and subsequently transferred to practical use in the outside world in ways not imagined by the inventors. As examples of such inventions Haldane[58] cites the telescope, cinematograph, barometer, gasometer, galvanometer and cream-separator. The microscope, as we have seen (p. 61), was perfected for the purposes of science and made available in its perfected form to the industrialist. We are here concerned not simply with the endless examples of practical applications of scientific knowledge to human affairs, but with the adaptation of actual instruments which were used by their inventors for the purpose of getting more knowledge about the universe. This exposes the fallacy of supposing, with J. G. Crowther, Hogben and others, that scientific results come only in response to material needs.

It would be reasonable to expect that one so insistent as Hogben on the directing influence of human need on science would exemplify that directing influence in his own research. I avoid the charge of making a personal attack

on him by saying straight away that his own research has been of high quality, judged from that purely scientific standpoint which seems to me the proper basis of assessment. No one is ever justified in prophesying that any discovery will never be of material use, but there are few subjects which seem less likely, in the existing state of knowledge, to find material application than some of those chosen by Hogben for his own research. As examples one may choose his work on the development of the egg in gall-flies[68, 69], ants[68], and dragon-flies[70]. These are pieces of sound work, fitting into, expanding and illuminating our knowledge of the maturation of eggs, and more especially the behaviour of chromosomes. I should be happy if the work stood to my credit instead of Hogben's; but it was not inspired by material human need nor has it served material human welfare.

In this age, in which even certain scientists misunderstand the nature of science, one can scarcely lay heavy blame on politicians for falling into the same errors. Nevertheless there are limits to philistinism, which even a politician should not transgress. A good example of such transgression is afforded by Moore-Brabazon's remarks about milk[103]: "The man who by his political efforts can get adequate milk to children deserves more of his fellow men than the inventor of the quantum theory; but in the narrow world of science, who gets the most attention and encouragement?" This remark is worth consideration, because it is an example of a fairly common attitude which should be exposed as false whenever it appears. I shall therefore analyse its falsity rather fully.

(1) By choosing milk and children as the subjects of his attack on science, Moore-Brabazon attempts to cause reason to be disturbed by emotion.

(2) Although cow's milk is good food, it is not a necessity

if the diet is varied. I have lived for two years among a well-nourished people who never drink milk except from their mothers' breasts. Many European children dislike milk after weaning and can easily be provided with alternative food-values in peace-time.

(3) The provision of milk supplies for those children who do not positively dislike it is good, but it is a matter which can be achieved by completely unoriginal people, as incapable of ever discovering anything as a politician. If those responsible for the provision of nourishment succeed in their work, they should be quietly commended for their ordinary efficiency. If they fail, they should be quietly replaced by others.

(4) It would be deliberate waste if original minds, gifted for research, were to undertake the job. If good scientists were to turn their attention to such matters, discovery would stop. What would be the present state of the health of the community (juvenile or adult) if men like Pasteur—an ardent believer in pure science—had been forced into the milk-distribution trade?

(5) If anyone says that the provision of milk for children is more important than the quantum theory, he must say also, to be consistent, that it is more important than the symphonies of Beethoven, the sculpture of Michelangelo or the writings of Shakespeare. Are we to become a nation of cultureless milkmen, because a few politicians cannot do a straightforward job requiring no spark of genius whatever?

(6) Planck's astonishing discovery that energy is not infinitely divisible is one of the most fundamental in science. It is difficult for the layman to comprehend, and seems contrary to "common sense". If the world is going to do without discoveries of this magnitude because politicians cannot appreciate them, science is going to stagnate.

(7) Moore-Brabazon calls the world of science "narrow"

Every fact about the universe which can be correlated with others into a system of demonstrable knowledge is the subject matter of science.

(8) Potential Plancks do not require any more "attention and encouragement" than Planck did himself when he was making his great discoveries, which he began to publish seventeen years before he received the Nobel Prize. Scientists are human beings and respond to appreciation shown by their colleagues, but they do not value the sort of "attention and encouragement" so much desired by politicians.

It is because loose talk like Moore-Brabazon's is so often directed against science nowadays, that this analysis has been undertaken. Most scientists regard it as beneath their dignity to reply, with the result that in the end science is actually threatened by uncomprehending philistines.

Those who have never experienced what Kropotkin called the "joy of scientific creation"[84] often regard love of science as something mystical and worthless. Actually these people, who fancy themselves as stern materialists, are much more mystical. If one carries their ideas to their logical conclusion, one arrives at nonsense. Everything, they pretend, must have material use. Everyone must concentrate wholly on nourishment, shelter, health and leisure: all else is useless. Nourishment, shelter, health and leisure thus become ends in themselves. They are not ends in themselves. People with the maximum amount of them are often the most miserable. To strive for them as though they were final ends is indeed mystical. Leisure particularly is misunderstood. By itself, with nothing to fill it, it is a positive evil, well illustrated in Sickert's painting, "Ennui", in the Tate Gallery. Never has leisure threatened so dangerously as now, when people are starting to demand passive amusement on the turning of a knob.

It is intolerable that some people should actually be

undernourished when there is enough food for all, but that can be put right by relatively few people without the whole population devoting every minute of life to thoughts of nothing except the material needs of man. Many people in all classes of the community who suffer great ill-health, even blindness or incurable disease, live full and worth-while lives just because to them nourishment, shelter, health and leisure are not ends in themselves. By concentrating on the real ends—art, music, literature, science, philosophy or the ethical part of religion—they find life worth living. Nothing is more useful in the final sense than the development of culture. Very few members of the community actually contribute to culture. Those who do so, do not want fame or wealth, but they want their work to go on. In the case of science, they have the special satisfaction, denied to musicians, of knowing that they not only serve the final ends of life but also build that secure and fruitful foundation on which technology can base itself to serve mankind in material ways. To misunderstand and therefore threaten science is to threaten both technology and culture.

Chapter 8

Science in the Age of Technology

WE live in an age in which one cannot fail to be impressed by the astounding achievements of technology. A concomitant of these achievements is the danger that we may unthinkingly claim to live in a particularly scientific age. In this chapter I am going to suggest various rather disconnected reasons for supposing that we should not lightly make this claim; but I want at the outset to make some remarks to avoid being misunderstood.

It may not be either possible or desirable to usher in an age in which everyone has a scientific mind. Literature and art would probably suffer, and there might be no benefit to various useful occupations. Even in subjects which are based on science, the scientific attitude is not absolutely necessary. An advanced medical student, entering not long ago an unfamiliar lecture-room at Oxford and seeing on the walls a number of drawings of rather obscure organisms unconnected with his own studies, remarked to a friend of mine, "A hell of a waste of time, learning about all these beasts". The "objects, materials and phenomena" of which Findlay wrote (see p. 84) were "a hell of a waste of time" to him. That need not make him a worse doctor. If I were ill, whether the illness were stomach-ache or cancer, I should not necessarily regard him as less able to give good advice than other doctors with a juster appreciation of the value of science. The full understanding of cancer, with everything

that that means to sufferers from the disease, will of course only become possible when students of what this man would call a waste of time have pushed the basic sciences far enough for understanding to be possible; but existing scientific knowledge can be applied, and applied effectively, by those who could not possibly be scientists themselves.

It is probable that many people who have not the scientific attitude would grasp it readily and enjoy the fruits of it throughout their lives if facilities brought it within their reach. There are probably such people in every class and occupation, and it is my purpose to suggest in the next chapter some plans whereby a scientific culture might be spread among suitable people throughout the population. Before doing this, it is necessary to give a few random examples from various lines of evidence which seem to show that we do not live in a scientific age. Nowadays people assume that everyone is a sort of scientist, and sometimes even say so categorically[90]. People who will readily admit that composers or artists have somewhat different talents from the rest of the community are apt to regard anyone as presumptuous who claims a comparable difference for scientists. Many people are learning science nowadays and passing into the world as scientists—people to whom it would never have occurred to investigate anything if their parents, following the fashion, had not pushed them into the subject. These people, who know that they closely resemble other people, will naturally assume that other scientists are similar to themselves; and they will be the heartiest and most genuine opponents of the idea that there is such a thing as aptitude for research. There is a real danger that mass-produced scientists may eventually swamp the genuine article. If economic conditions or fashion were to make a hundred times as many people take up a musical

career as happens today, many with no real musical ability would become composers. A lot of them would no doubt become proficient at such tasks as the arrangement of parts for a military band, but there would be no genuine inspiration.

The idea that we live in a scientific age is fostered artificially in various ways. We talk airily to our neighbour at a dinner-party about the second law of thermodynamics, but we only do this because we trust her not to let us down by asking whether we know what the first is. People talk freely and unaffectedly of ohms, volts and microfarads; but ask anyone who does so to find the resistance of a wire from the definition of an ohm, and see how he sets about it. An ohm is a thousand million times the resistance to the passage of an electric current shown by a wire which requires one erg of work each second to force through it a current which, flowing along a wire one centimetre long bent into a circular arc of radius one centimetre, exerts a force of one dyne on a unit magnetic pole placed at the centre of the circle, a unit magnetic pole being one that, when placed one centimetre from another unit pole, exerts on it a force of one dyne. I have not the faintest idea of how to begin, but I draw comfort from the statement[2] that it would take weeks of refined experiment by the most skilled observers to do it. Now the meaning of a volt depends on the meaning of an ohm, and is therefore more complex again, and to understand farads and microfarads one must understand not only the volt but also the coulomb. Of course we can all measure volts by the simplest possible means, but it is a very different matter to understand what the word means or the principles on which the calibration of the voltmeter depends.

It is not the bandying-about of scientific words which characterizes a scientific age. Russell[118] maintains that belief in reason reached its maximum in the 'sixties. Today

there is evidence that about 40 per cent of the population of Britain has some degree of belief or interest in astrology. Harrisson[60], after studying hundreds of comments and conversations, says that "it is impossible to doubt that astrology is now a very considerable influence in determining the minor decisions of many private lives, and an appreciable contributory factor in influencing attitudes to wider, international events".

I was once at a public lecture on first aid, and the lecturer was explaining a method of artificial respiration. He stated that the operator should keep his fingers together. Immediately there was an outcry from the audience: people called out that the fingers should be kept apart. The lecturer now quoted a book of first aid in support of his argument: immediately members of the audience quoted another book in support of theirs. The course of lectures was not going to be followed by an examination, and there was therefore no set book to which it was profitable to adhere; but this did not affect people's behaviour. It now became apparent that some members of the audience had read the book quoted by the lecturer, and fierce arguments ensued as to whether the books said this or that. Chaos reigned for five or ten minutes. At last quiet was restored and the lecture started again, without anybody engaged in the argument having enquired how the separation or approximation of the fingers might influence the restoration of respiration, or suggested any way in which it could do so.

The day on which a student first starts to learn genetics, he is told about the inheritance of colour in Andalusian fowls. If Blue Andalusians are mated together, the progeny will tend to be in the proportion of one black to two blue to one speckled or "splashed" white, a close approximation to these proportions being obtained if a large number of chicks are raised. If, however, one of the blacks is mated with a splashed

white, all the offspring will be of the desired "blue" colour (which is actually a slate-grey). The interpretation of these demonstrable facts forms a basis for the understanding of the principles of heredity. A special society[17], however, governs the affairs of the Blue Andalusian fowl, and the proceedings of such societies are based not upon science, but upon that particular variety of opposition to inductive methods which is called common sense. "It stands to reason", a breeder told a geneticist[31], "that if you continue to breed from the Andalusians you will ultimately fix the strain. It is common sense." Common sense dictated the destinies of the Blue Andalusians for fifty years. The black and splashed white progeny were killed or sold as "wasters"[123] and half the progeny only were Blue Andalusians. If the "wasters" had been kept and bred together, all the progeny would have been Blues; but this would not have satisfied the Poultry Club Council, which requires that the breed must have thoroughbred characteristics to come up to its Standard of Perfection.

When a discovery in pure science is reported in the popular press, the writer often either makes fun of it or feels bound to invent material ways in which mankind will benefit. It is assumed that readers will not be interested in science, except as a subject for fun or practical profit. Scientific films exhibited at public cinemas are usually accompanied by facetious commentaries.

Belief in a magical relation between whiteness and purity is strong enough to force the Government, at a time when national survival depends on the best use of food and money, to make elaborate arrangements to have the vitamins removed from wheat and subsequently returned to the flour. In putting forward deliberate propaganda it is possible to assume that a modern audience will not want to use reason at all. "Do you think for a moment", asked Quentin Rey-

nolds[113] in a BBC broadcast, "that a man bearing the name of Winston Churchill will ever bend his knee to anyone named Schickelgruber?" This was not a private message to Hitler, but was broadcast at the time when the greatest number of British listeners would be listening. We are still in the age of magic.

It is not only among the general public that disregard of science and scientific method thrives in this technological age. I once knew a man who was interested in the fluctuations in abundance of a certain insect. He searched back in history for anything bearing on the subject. His research took him to ancient China, and to a time when war was in progress there. He tried to guess the effect of that war on the likelihood that the ancient Chinese would notice and record changes in the numbers of the insect. He wanted to use his guess in a scientific account of periodical fluctuations in abundance.

Those who have not studied the history of science are apt to think that apart from a few geniuses whose names are household words, there was little science till a hundred years ago. A fleeting glance through the two centuries before 1840 will show how wrong this impression is. Even if one excludes the most familiar names, restricts oneself to physics and merely dips casually here and there into the subject, it will not be found possible to retain the idea that science was sleeping in those two hundred years. At the beginning of that period von Guericke was experimenting with vacua and air-pumps. Later in the seventeeth century Mariotte discovered the law of the compressibility of gases independently of Boyle. During the first half of the next century Cuneus discovered the electrical principle which led to the Leyden jar, and in the process of doing so got such an electric shock—the first one, apart from lightning, ever felt by man—that he announced that he "would not, for the crown of

France, expose himself to a second such shock"[2]. The very next year Watson, at Shooters Hill, near London was sending an electric shock from a Leyden jar through two miles of wire supported by wooden poles. In 1757 Dollond invented achromatic lenses and made possible the wonderful optical instruments of today. About the turn of the century Monge, accompanying Napoleon on his Egyptian campaign, explained the phenomenon of mirage, and Chladni investigated the vibration of strings, rods and plates and laid the foundation of modern acoustics. Malus discovered in 1809 that light is polarized by reflection. A dozen years later Seebeck discovered how an electric current may be produced by heating the junction of two wires made of different materials, and thus originated the thermopile. In 1827 Colladon and Sturm were measuring the velocity of sound in water by experiments made with the aid of two boats moored a known distance apart in the lake of Geneva. In 1834 Lenz announced his law relating the direction of an induced electric current to the movement which induced it.

If an authority were to pursue the history of physics in those two centuries, omitting all the work done by the most famous men, a volume could be filled; and if all sciences were included, many volumes. A glimpse has been enough, but another view-point shows that science was wide awake during those two centuries: the great men discovered the same things about the same time. Charles discovered in 1786 the law of the expansion of gases when heated which still bears his name. He omitted to make his discovery known, and Dalton rediscovered it in 1801 and Gay-Lussac the next year.

Anyone who cares to look at the history of scientific thought will find that right through the centuries there were people groping towards the attempt to obtain knowledge by observation, experiment and reason. Hippocrates, and a

little later Aristotle, were already developing the method of science about twenty-three centuries ago, the former in pathology and the latter in biology. How much Aristotle owed to Hippocrates, it is impossible to say: he only refers to him once in his writings[12]. From that time to the present day it has been open to people to use the scientific method, and it is perplexing to remember that despite this the great majority of the people of all countries have always preferred to be guided by tradition, authority, desire or magic. Hippocrates and Aristotle had to think out the method of science for themselves, and the other great scientific philosophers of past ages had little to encourage them in what they read. Today there is a profusion of books on science, but the effect in producing a scientific culture is small. People "do stinks" at school; they "make" chlorine or dissect an earthworm: but there is little realization of the great principles which, in the hands of an infinitesimal fraction of the human race, have made possible the building up of such a vast body of demonstrable knowledge.

Religion has probably played a part in preventing the growth of scientific culture, for in every religion except Unitarianism the use of reason is only accepted with certain safeguards. It must be said at once that great scientists, from Pasteur downwards, have not rarely been religious, but nevertheless formal religion has probably been a force acting in opposition to a wide understanding of the methods of science. Fascism, Nazism and Communism, which have something in common with religious movements, are also a detrimental force because they put other values above truth. In science there is no loyalty to creed, party or class: only to demonstrable truth and reason.

Chapter 9

People as Scientists

"He who has once in his life experienced this joy of scientific creation will never forget it; he will be longing to renew it; and he cannot but feel with pain that this sort of happiness is the lot of so few of us, while so many could also live through it—on a small or on a grand scale—if scientific methods and leisure were not limited to a handful of men." KROPOTKIN[84]

NOT everyone's mind provides a fertile soil for the growth of science, but the most unexpected people sometimes respond surprisingly to the sowing of a seed. Go for a country walk with a non-scientific friend and suggest tentatively that the hills and valleys are not arranged haphazard, but result from the geological history of the world in ancient times. You are likely to be deluged with questions, and unless you happen to be an authority on the local geology, you may find yourself quite at a loss to answer many of them. The intelligent ignorant person always asks the best and hardest questions, because his mind has not been taught to follow a rut.

A wider spread of scientific culture would not only bring happiness to many who are not and cannot become professional scientists: it would benefit the professional scientists themselves. Indeed, one can scarcely speak of a culture when the activity is confined to those who make their living from it. A cultured public is a necessity for good literature and music. It is valuable also for pictorial art, though here the relation between what might be called producer and consumer is much less satisfactory. People may seek to make

money by attaching a rarity-value to the works of a certain artist, or falsely boost his virtues for the same purpose, so that a carefully fostered deceit may vitiate public taste. A living artist may spoil the rarity-value of his works by painting more pictures: he is better dead. An unfortunate painter may even see it mentioned in print[139] that his work fetches more per square inch than that of any other painter has ever fetched during the painter's lifetime. Luckily such degradation of culture can never afflict the scientist any more than the writer or musician, for the work of all three can be printed and reprinted indefinitely without detriment, and there is no scope for the deliberate attachment of false values. The scientist is generally appreciative of appreciation, if it is based upon understanding: fame cannot help him. If there were a more widespread scientific culture, professional and amateur scientists could render one another the sort of mutual help given by composer and musical public. Just as amateur musicians play music, so also amateur scientists can actively pursue science; but whereas an amateur musician is unlikely to add anything permanent to music beyond his own contribution to the spread of musical culture, an amateur scientist can make genuine discoveries, and these will be accepted into the general body of knowledge and become the foundations for further research.

Amateur science is regarded with some disfavour, even contempt, today. It was not always so. Einstein and Infeld[43] have remarked that "nearly all the fundamental work concerned with the nature of heat" was done by amateur physicists. People tend to forget that one of the greatest scientists of all times, Charles Darwin, was an amateur. He was, of course, a fairly rich man. Rich men are much rarer nowadays, and no one would wish to suggest a culture specially designed for them. Wealth, however, is by no

means a necessity for the amateur scientist. Anyone who thinks it is should read the life-story of Hugh Miller[102], the quarryman, stone-mason and accountant, who was a well-known geologist and palaeontologist and author of "The Old Red Sandstone"[101]. A shop-keeper of Thurso helped to furnish him with the specimens used in his work. Miller wrote enthusiastically of another amateur scientist as "one of the best . . . geologists in Forfarshire"[102]. That would not be a likely description of anyone today. The words were written in the second half of the nineteenth century, when science probably progressed more rapidly than ever before or since, and was widely valued as an end in itself.

What can be done to stimulate a wider interest in science today?

It may be suggested that the approach is wrong. Nothing could be more unlikely to produce a scientist than the knowledge that one must "do" certain sciences for the school certificate. The first requirement is that the young boy or girl should get to know something of the scope and method of science. These subjects will probably be found harder to teach than the bare facts of a science, because the teacher may know less about them. The teaching, however, need not be elaborate. The principles of observation, experiment and inductive reasoning are not complex, and quite a small child can be made to understand the difference between objective and subjective experience. No great knowledge of the various sciences is required if one is only going to say what sorts of subjects are covered by each. It will, of course, be necessary to show that the scientist cares nothing for authority or tradition, and it may not be found quite easy to reconcile this, in the untrained minds of the pupils, with the respect properly shown by scientists for the great discoverers of all times. The life-stories of the greatest discoverers provide a human background which may give an

interest in science to those children who find the plain facts rather dry.

If the object of the teacher is to find out which of the pupils is the best adapted for further training in science, the simplest work is the best. It is no good to try to rouse a false interest by giving a necessarily over-simplified account of some wonderful technological achievement like wireless telephony. It would be far better to teach a child how to weigh as accurately as the available apparatus will allow, or to measure or count or compare familiar natural objects. Elementary schools cannot afford to purchase elaborate scientific apparatus, but it may be suggested that quite good balances and microscopes might be circulated from school to school, so that there would be an occasional opportunity for each child to work with real instruments under the supervision of the teacher. It should not be hard to spot the child who delights in deftness and accuracy and is worth starting on a scientific career. At present rich people have a much greater possibility of interesting their children in science than poor, and there is probably an untapped wealth of talent in all classes which needs a little encouragement if it is to be found. It is true that a Faraday will rise from any circumstances, but a great part of science is the work of much lesser but very good men, who would not have been scientists at all if their parents had not been fairly rich.

The waste of talent by non-recognition is not overcome by the scholarship system. If talent in science announced itself as early and unmistakably as musical talent, the scholarship system would suffice; but there is a tendency for this system to favour the precocious, and scientists are not particularly precocious. When Bateson, the eminent geneticist, was seventeen years old, the headmaster of his school wrote of him, "it is very doubtful whether so vague and aimless a boy will profit by University life"[14]. No one

thought Charles Darwin clever as a child, boy or young man. J. J. Lister, who invented the principle on which all modern high-power object-glasses for microscopes are constructed, did not make any discovery until he was thirty-eight years old[86a]. Success as a discoverer probably depends much more upon inclination and perseverance than on unusual cleverness in childhood. With reasonably promising material, intelligence will develop as the necessity for it arises.

The wider and more unspecialized the teaching of science in schools can be, the better, provided that there is no accompaniment of inaccuracy. If a boy or girl in the 'teens shows special enthusiasm for a limited field, as often happens, the development of that field can well be left to out-of-school hours. The product of the school should not be a prodigy of learning in one science, ignorant of the methods and scope of science as a whole and its position in human culture.

When I was a boy at school, I was spending one half-holiday afternoon examining the eye of a beetle with my microscope. No biology was taught: indeed, it was a rare subject in schools at that time. The headmaster chanced to pass by and asked me what I was doing. The investigation was not approved. I was told that I was wasting my time and was sent off forthwith to spend my half-holiday doing someting useful, mowing the lawn. I was determined to study zoology and devoted every available moment to it despite the lack of encouragement at school. At last my real opportunity came, at Oxford. The Warden of my College sent for me and asked me what subject I wanted to study. "Zoology", I replied. "Would it not be better", asked the Warden, "to study something useful, such as medicine?" I was too inexperienced and shy to explain to the man who had taken a triple first class (in classics, mathematics and theology) that medicine stands on the basic sciences like a house on its

foundations and that science has a value as an end in itself; but I studied zoology.

Some amount of discouragement in the later years of a boy's or girl's development is probably not a bad thing: it will show up the enthusiast. It would be sad to see the research laboratories of pure science cluttered up with non-enthusiasts. J. G. Crowther[26] has stated that the majority of British scientists would probably be glad to resign from research permanently, in exchange for high administrative positions. I can only say that I cannot disprove this statement statistically, but it is absolutely contrary to my experience of research scientists, whose enthusiasm for their work is only comparable to that of the true musician or artist for his. If there were too much encouragement the wrong people might be led astray into thinking they had the gifts of an investigator. That great scientist, Banting, discoverer of insulin, believed that people should only take up research if they had an impelling urge to do so. "Do not enter upon research", he told the students of Edinburgh University[22], "unless you cannot help it." This is memorable advice.

Of those who have become fascinated with science as children, some will pass on to a scientific career and others will take up other occupations and retain their interest. There are many people in other occupations today who are interested in science, though probably less than in the second half of the last century. What can be done to let them take a fuller share in scientific culture?

There are certain sciences which are particularly suited to the amateur. Almost no research in chemistry is carried out today by amateurs, perhaps none at all. I do not believe that amateur chemistry is a modern impossibility, but clearly other fields are more inviting, especially those subjects which, as has been shown in an earlier chapter, may be conveniently grouped together as natural history.

It is in unexplored country that many branches of natural history can best be studied; but exploration cannot be for everyone, and nature reserves are nearly as good for many purposes. The nature reserves of North America are magnificent examples of what can be done by freeing a small fraction of a country from commercial exploitation in the interests of science and recreation. In Europe there are such fine reserves as the Swiss National Park near Zernez in the Engadine[18], where natural scenery, flora and fauna are preserved for enjoyment and study by the people of today and by posterity. The National Trust has made a start in Great Britain. It is greatly to be hoped that after the war more national nature reserves may be started in various parts of Great Britain, for the use of professional and amateur scientists and of the general public. Some could be quite small, perhaps only a few acres in extent in certain carefully chosen places; others covering wide areas of country of little commercial value. In each a small central part should be set aside and no one allowed to enter except serious students, amateur or professional.

The scientific study of natural environments is in its infancy. The evolution of plants and animals took place in natural environments, and evolution can never be understood unless such places are set aside for study. Not only in industrial countries but also through most of the world man is effacing natural vegetation and placing beyond the hope of study those complex interrelations of plants and animals which have resulted in the evolution of living organisms as we know them today[65]. What is wanted is not the artificial protection of a few selected rare species in special sanctuaries, but real nature reserves where the interrelations of organisms may be exhibited without human interference. The extinction of rare species is regrettable, but probably it does not generally have much effect on the flora and fauna

as a whole. The introduction of a few exotic species may, on the contrary, completely upset the natural conditions of life. Nature reserves will be useless in a country if the deliberate setting free of species introduced from abroad is permitted, for they will be likely to spread to the reserve and it may be found impossible to eradicate them. Great Britain is rather fortunate in this respect. Not many people have followed the bad example of the Duke of Bedford, the chief introducer of the grey squirrel, whose natural home is the central and eastern parts of the United States and south-eastern Canada[96, 97].

Other parts of the world have suffered heavily. One thinks with despair of the man who got a medal for introducing rabbits into Australia, and of all those, undecorated but assiduous, who wrecked the intensely interesting fauna of New Zealand by introductions. A walk through that country now reveals a preponderance of introduced birds. No other place in the world had such an extraordinary bird-fauna as the Hawaiian Islands. I well remember stepping ashore there optimistically, quite forgetting that the vandal had been on the spot long before. If a mad millionaire decided to spend his fortune in destroying Wallace's line by transporting Oriental species to the east of it and Australian to the west, his error would differ in degree but not in kind from that of a person who deliberately and capriciously tries to naturalize and set free any exotic species anywhere.

It is sometimes argued that the introduction of an exotic species is natural because it occurs; that it is an experiment, and therefore interesting. Suppose that the charwoman who cleans a chemistry professor's laboratory thinks it fun to mix the contents of two of his test-tubes. Let us imagine that when he expostulates, she tries the argument on him. "Everything that has happened is natural", she says; "the contents of the two tubes have reacted in natural ways, and

you ought to be interested in studying the reactions." I shall not elaborate the professor's answer; but in a cooler moment he will reflect that the only possible scientific study of the incident would be a psychological investigation of the caprice which made her interfere so thoughtlessly and catastrophically with his research. The biologist has often cause to think these thoughts.

There is every degree of interference with natural habitats from the breaking of a twig as one pushes one's way through an unexplored tropical forest to the conversion of countryside into a city. Perfectly natural conditions, in the sense that they are absolutely unaffected by the will of man, can seldom be provided in a nature reserve, but the best is the enemy of the good, and very good nature reserves could be set aside if counsels of perfection were not allowed to bar the way. A sharp distinction must be drawn, nevertheless, between a true nature reserve and old-fashioned countryside. The scientist, as such, has no particular anxiety to preserve a certain stage in the evolution of agriculture because it is pleasant to look at old farmsteads and their surroundings. It certainly is pleasant, but it is not science.

Today it has become especially desirable that there should be a re-awakening of interest in natural history. In the growing science of ecology[44, 45] there can well be co-operation between professional and amateur scientists, to the benefit of both. The British Trust for Ornithology is already encouraging such co-operation in its own field. Genetics, long thought to be a science of the laboratory, garden, and animal breeding establishment, is not going to remain for ever so tightly constricted. E. B. Ford, the originator of a movement for the study of genetics in natural habitats, has already made important studies of the actual occurrence of evolution in our own times[49], and has not hesitated to collaborate with amateur naturalists. Studies of this kind

could probably be multiplied and would result in great advances in knowledge. Everywhere problems seek solution: we are ignorant of much that concerns the behaviour of the very commonest animals. An amateur naturalist, Eliot Howard, is one of the foremost authorities on the behaviour of wild animals and in particular on territory in bird-life and the significance of bird-song[74, 75].

The non-professional scientist must always strive to keep his interests as wide and deep as possible. Merely to know the names of organisms in a limited group is scarcely more scientific than stamp-collecting. Private collections are generally useless; collections should only be made for museums so that the specimens will be available to others. It is far better to observe than to collect. I have seen a printed discussion of whether the collector of birds' eggs should know anything about what lies within the shell. Anyone who limits himself to the study of the shell ignores the significance of what he is studying, and scarcely ever does the collector even study the shell itself, its minute structure, the chemistry of its pigments, or the methods of its formation.

Many naturalists are extraordinarily limited in their outlook, without realizing the fact. Some of them, intensely interested in the outsides of birds, are surprised if they discover that a professional zoologist is ignorant of some feature of the coloration or habits of a bird with which they are familiar. It is as though a man devoted his life to the study of the external appearance of green bridges, and was astonished, on discussion of his favourite theme with a professional engineer, to discover that the latter was totally ignorant of the existence of a certain green bridge in Venezuela. Fisher's "Birds as animals"[48] provides a healthy corrective to the narrow outlook of some students of bird life. (It may be remarked that the title which he chose sug-

gested those which I have adopted for two chapters of this book.)

Amateur naturalists need not all concern themselves with problems of great complexity. A little story will illustrate this.

A trader on the coast of Labrador, George Cartwright, brought some rabbits with him from England. On 24th April 1778, he wrote in his diary an account of a doe giving birth to young in his dining-room. He made observations on the development of the young, and recorded that on the eleventh day they "began to see". His diary was subsequently published[21].

More than a century and a half have gone past since George Cartwright observed his rabbits. Ask any zoologist today at what age the eyes of the young rabbit open. The matter is not entirely insignificant, because the rabbit is so much used as a type in teaching zoology. The zoologist will at once refer you to Barrett-Hamilton's account of British mammals[13]. This author, however, got his information from a footnote in a book by Harting published in 1898[62]. Although Harting does not give a reference, he must have been quoting from a book by Daniel published in 1801[29], for every particular as to length of pregnancy, age when ears can be moved, age when eyes open, and age when ears can be erected, is exactly the same. Daniel, however, never claimed to be the original observer: he got his information straight from Cartwright. So we are back again in Cartwright's dining-room in Labrador in 1778, apparently the place of origin of the best modern information on the age at which the rabbit's eyes open. The information is based on the study of a single litter of tame specimens in an extraordinary environment. One is reminded of the scholars of long ago, who sought to settle once and for all the vexed question of whether mares have canine teeth, not by looking to see, but by reference to the works of Aristotle. Lest anyone should hurry off to

study the eye-opening of young rabbits, I must give three warnings. First, the practical difficulties are not as small as might be thought; secondly, statistical methods must be used; and thirdly, one should make sure that some tedious German has not already found the mean age of eye-opening to the nearest minute.

To encourage the growth of scientific culture a new journal and a new society seem necessary. There is no British journal of general science suitable for reading by amateurs. "Nature" is now the only general scientific journal published in Britain.* Every scientist will admit its usefulness, but it contains so much that is incomprehensible outside one's own province of knowledge, that it can scarcely claim to present science as a whole to either professional or amateur. Further, it has become increasingly interested in technology, presumably because it is read by more technologists than scientists. The very name of the journal has thus tended to lose something of its meaning. Although the extract from Wordsworth is still printed on the cover every week,

> "To the solid ground
> Of nature trusts the Mind that builds for aye,"

yet one imagines that a good many minds which eagerly devour its pages are building for the immediate future and trusting more to business than to Nature. It was by a curious chance that at the beginning of 1935 Nature lost her capital letter in the little verse (while mind acquired one); for it is since about that time that the fashion has arisen to confound science with technology and to overstress practical applications at the expense of basic knowledge.

A journal of scientific culture would be readable throughout by any professional or amateur scientist, and would keep

* The *School Science Review* is excellent, but addressed to a special group of readers.

the interests of both wide and lively. It would not be impossible to write about science in a generally intelligible way, for there are excellent examples of fairly recent books on scientific subjects which the general reader can study with interest and which are profitable also to scientists working in different sciences: for instance, Jeans on acoustics[82], Findlay on chemistry[47], Parsons on biochemistry[107], Skene on British plants[121], Ford on genetics[50], Tansley on psychology[126], and Trueman on the geological basis of scenery[135]. Darwin wrote particularly intelligibly and the public seized what he wrote with avidity; every copy of the first edition of "The Origin of Species" and 5,267 copies of "The Expression of the Emotions in man and animals" were sold on the respective days of publication[36]. In this twentieth century there are branches of science in which new advances in knowledge can be published in quite an intelligible form: one may instance Elton's "Animal Ecology and Evolution"[44], Fraser Darling's "Bird Flocks and the Breeding Cycle"[30] and Eliot Howard's "Territory in Bird Life"[74].

The books that I have mentioned show that a general journal of scientific culture is a possibility, and one may earnestly hope that after the war such a journal will be founded. One may hope also for the formation of a society for unprofessional science, to help amateurs in all matters connected with their interests, and especially in arranging for mutual help between them and professional scientists. The Fellowship of the Royal Society is the highest honour that is conferred on scientists in this country, and there is every reason to believe that the existence of this special honour is a stimulus to many research workers. It is very difficult nowadays for an amateur to make such a large contribution to knowledge as to gain this Fellowship, but the principle of formal recognition of good research could be extended to the proposed new society, which might

confer Fellowship for investigations of particular merit, while allowing membership to all with the interests of science at heart. It is unfortunate that the amateur scientist should so often go without proper recognition, while people lacking the true spirit of science get themselves labelled with degrees.

There are many ways in which the living culture of science could be encouraged, and only a few can be briefly touched on here. One last suggestion may be put forward. People with active brains who enter a scientific museum are overwhelmed by the superabundance of what is put before them: they do not know which way to look: a few cubic feet of space would occupy hours of study, and from every side other exhibits call with equal insistence. It is as though one entered a gigantic lecture-room in which all the lectures of a three-year course were being delivered simultaneously. Is it not possible that public museums are wrongly arranged? Might not the greater part of the public space be devoted to a few exhibits, and these constantly changed and the changes announced in the local press? The number of exhibits would be as low as was compatible with everyone getting a good view. Behind the scenes there would be the same wealth of material as before, readily available to the serious student, amateur or professional. This scheme would stop the aimless wandering about that one notices in museums, and the would-be wanderer might leave the building with a few definite new thoughts in his head, instead of a haze of ill-digested information.

The suggestions put forward in this chapter for the development of a wider and deeper scientific culture are crude and tentative. I hope that others, aware of their crudity and more far-seeing than I, but no less anxious that the culture of science should prosper, will put forward better ideas and transform them into realities.

Chapter 10

Prospect

THIS book has been written in the hope that it may exert a little influence on people's attitude to science during the period of reconstruction after the war. So many books have been written lately by those who equate science with technology and wish that research should be centrally planned, that the layman might easily be forgiven for thinking that these books represent the views of the majority of scientists. Unfortunately the majority say nothing and let their case go by default. Books and speeches pour forth from the "planners". The British Association for the Advancement of Science organizes a so-called "conference" at which all the leaders of the "planning" party deliver addresses. During the whole of six sessions lasting three days, no one is allowed to speak except those chosen in advance by the organizers, and none of the leaders of the movement for freedom in science is chosen. A "Charter" is produced by the Association, which includes the words, "The basic principles of science . . . are influenced by the progressive needs of humanity"[57],* as though the search for objective truth were futile. "Nature" moves with what its editors think to be the tide. "The Scientific Worker" adds its influence.

Still the great majority of scientists make no public

* Since the holding of the conference the Association has rewritten the sentence, but the fact that it could be solemnly pronounced by the President and then published shows to what depths a body supposed to represent science may sink.

utterance. "It can't happen here", they say in private; "leave us alone; we only want to get on with our research." Exactly; so do I. It is because I want scientists to be free to do their own research that I have written this book. They will not be free if they do nothing and let those who would dictate their research for them do all the talking and writing. Only one little book has appeared in opposition to the planners' library. Polanyi's "The Contempt of Freedom"[111] contains a masterly short statement of the case for freedom in science.*

There is only one aspect of politics which directly concerns scientists as such. When their freedom to pursue their own research is at stake, they are directly concerned, and they are in a position to form sounder opinions on that subject than anybody else. They should make their opinions heard. In other matters it is often best for them to leave politics alone. A research worker cannot obtain the quietude necessary for the fulfilment of his duty—that of discovering demonstrable truth—if he throws himself into the stress of party politics. If he goes so far as to use scientific prestige to get political power, he prostitutes his talent. Hopkins, a pioneer of vitamin research and a practical benefactor of humanity, said that it is impossible not to sympathize with the view, commonly held by scientists, that they will be more useful if they continue their chosen work in its proper environment, than if they give up time to the question of the social implications of their calling[73].

The planners adopt a pharisaical air of ethical superiority. They presume to give the impression that they alone are concerned with the welfare of humanity, while other scientists selfishly study nothing but their own inclinations and convenience. Since the planners raise the question of

* See also Polanyi's "The growth of thought in society" (*Economica*, Nov., 1941).

ethics, they must be answered. Everyone, scientist or not, has the opportunity every day of his life to promote the welfare of others in inconspicuous ways. The scientist who quietly and unostentatiously does good to others by simple kindness, thoughtfulness and justice is more likely to be a useful member of the community than one who loudly boasts his social conscience and his determination to improve other people's lot by seeing that it is dictated to them. Whereas political stress dulls the scientific mind and makes it less capable of originating new ideas, the simple unadvertised virtues have no such effect. Simple, good, hate-free men like Charles Darwin and Michael Faraday are inspiring examples to all who come in contact with them or who read the stories of their lives.

One hopes that the period of reconstruction will provide a fairer share of the good things of the world for everyone and more equal opportunities for each person to serve the community in the way for which he happens to be best fitted. More equal opportunities for members of all classes to live the scientific life would give great promise for the advance of science. Great scientists have arisen from all classes. Even if it be true that genius will always manifest itself, yet, as we have seen, an enormous contribution to scientific research is made by talented people who are much less than geniuses. Such people can best be recognized and secured by giving equal opportunity to all.

The coming of a real democracy, then, would bring a great hope for science. It would also bring a danger. That danger must be faced, though I am aware that what I am about to say on this subject lies patently open to misconstruction and partial quotation by those who do not want to face the facts.

Few superstitions have less scientific foundation than snobbery. That anyone should claim special privileges

because he was born in a certain class is ridiculous. If in fact he is innately superior, then his superiority should manifest itself without the necessity for privilege. Half a century ago, snobs fawned upon the aristocracy and the richer classes of the community. Scientific analysis of the social distribution of innate intelligence suggests that the professional classes are on the average somewhat superior in this respect[11, 21a, 21b], but there is so much overlap between all classes that the scientific basis of professional-class snobbery is small, so far as innate qualities are concerned. Today snobbery rears its ugly head again, but now it turns it in the opposite direction, and the tendency is to fawn upon the factory-workers. No scientific evidence supports this kind of snobbery, which is just as baseless as the others. Harrisson has done well to expose its falsity[61]. To try to obtain advantage or security for oneself by falsely attributing special innate virtue to any class is contemptible.

In the professional class there is often a tradition of respect for certain ends-in-themselves, such as art, music and literature, and so the children tend to grow up with a feeling that such ends have a primary human value. If the child of a factory-worker were to grow up in the same surroundings, he would undoubtedly tend to respect those ends in the same way. Actually he does not generally grow up in surroundings where culture is much respected (though of course there are splendid exceptions). That is the fault neither of the parent nor of the child, but it is a fact; and it has resulted in the adults of the poorer people generally having less respect for culture than the members of the professional classes.

Scientific culture has certain advantages not shared by artistic and literary culture. When the historians of the distant future look back on the pitiful struggles of man in the years between the two great wars, they will note with

sympathetic understanding that many of the artists, composers and writers were jolted by their environment to produce work which suited it but was without lasting value. They will know the reason for the child-like and schizophrenic paintings, grotesque statues, cacophonous music and chaotic literature of the period. They will recognize that the scientists of the time, in contrast, went solidly ahead—more slowly, probably, than in the quieter years before, yet straight ahead—to contribute, as always, to the eternal value of truth. Because science is uninfluenced, except in speed of progress, by passing phases in the external world, because even an environment that tends to shatter artists and composers and writers cannot throw science off its balance, science may perhaps claim to be a unique manifestation of the human mind. It progresses more certainly than other cultures because its progress is more necessarily additive. Its potentialities are unbounded, for each generation starts where the one before left off. Only two things can kill scientific progress. Those two are "planning" and the confusion of science with technology (a confusion which is comparable to finding nothing in music but box-office receipts, musicians' salaries and a stimulus to the martial spirit, and which would in the long run be as damaging to technology as to science).

If a country suddenly puts the government into the hands of the poorer members of the community, culture of all kinds is genuinely threatened unless it has already spread throughout the population. The Russian revolution provides an instance. Interest in the ballet pervaded all classes in the big cities before the revolution, and ballet survived and still flourishes. Science, never very strong and a closed book to the poor, was struck a staggering blow. Although vast sums are said to have been spent on Soviet science, the return (in science as distinct from technology) has been poor. A few

British scientists take every opportunity to praise Soviet science. Haldane[59] feels it necessary to tell us that certain Soviet scientists have not lost their jobs, so far as he knows, although they hold views (held almost universally by the geneticists of the rest of the world) which conflict with views expressed by Engels. We are supposed to admire the toleration which admits discreet opposition to the sacred writings. Even Haldane has to admit that the genetical view favoured by Soviet authority "appears to be untrue in the light of actual biological research". One cannot fail to ask oneself whether the same people who praise Soviet science so loudly would have bothered to do so or to make such careful excuses for its shortcomings[16, 26], if the same scientific output had come from a non-communist state. The praise springs from political, not scientific enthusiasm. It must be remembered that the making of many guns, tanks and aeroplanes is a technological achievement, which has no connexion with the advance of scientific research.

At the time of the French revolution, the president of the court which sentenced one of the greatest chemists of all time to death remarked, "The republic has no need for scholars"[94]. (Lavoisier was executed the same day, though guiltless of any crime.) One hundred and forty-seven years later the Soviet ambassador told the British Association for the Advancement of Science (on 27th September 1941), "We in the Soviet Union never believed in pure science." If the poorer people in this country were to determine its internal policy without accepting advice from others, culture of all kinds would for a time be endangered. The phrase scientific culture, or science as an end in itself, would not be in the least understood. Technology only would be accepted. Science would be dealt a heavy blow, from which technology would eventually suffer as heavily as science itself. A warning from scientists is urgently necessary, and

instead of the warning there comes a steady flow of propaganda in the wrong direction, urging the smothering of science under technology and the substitution of planning for free enquiry. A large part of the propaganda is poured out by those who have themselves been scientific research workers, which would be hard to understand if we could not find clear evidence of political emotion quite obscuring clarity of scientific vision.

If people who have had the good fortune to grow up in an environment in which culture is respected would give the warning in time, they would serve the community well. If only snobbery could be eliminated, culture of all kinds spread throughout the community, and suitable talented people taken freely from all classes to enrich all professions, civilization might progress as never before in the history of the world. Everyone in a true democracy would have the opportunity to live a full life according to his innate capacities. Those gifted people who found themselves attracted towards immediately practical pursuits would find an absorbing life-work in technology. Those of a less practical disposition would serve the community equally well as scientific research workers or creators of culture in some other sphere. Music, art, literature, philosophy and science would be widely appreciated among those not talented enough to be creators themselves. I do not agree with the pessimism of Raymond Mortimer[106], when he says that he sees no grounds for the assumption that the great majority of human beings are potentially capable of enjoying the arduous exercise of their intellects and æsthetic sensibilities. The great majority of children, I think, are capable of being trained to appreciate some sort of culture.

True appreciation, based on real understanding and widely spread through the community, would react on the creators to inspire further creative effort. With free enquiry,

free criticism, lively discussion and the opportunity given to all to understand and enjoy the great gifts that culture can bring, a genuine democracy would produce a flourishing civilization in which each person would be given the chance to feel that life was full and worth-while and exciting. Widely diverse in tastes and interests and talent, each man and woman could find a satisfying niche.

Another and a vastly different prospect looms ahead. An ugly new god called the state demands worship. Nourishment, shelter, health and leisure are falsely regarded as ends in themselves. Culture is looked down on with contempt. Science is equated with technology and both decay. Individualism and free enquiry are ridiculed. Everything is planned from "above". A dreary uniformity descends. Each person is a cog in a vast machine, grinding towards ends lacking all higher human values.

It is for you to choose.

List of References

(1) ADAIR, F. E. 1931. *Cancer.* Lippincott, London.

(2) ALDOUS, J. C. P. 1910. *An elementary course of physics.* Macmillan, London.

(3) ALEXANDER, S. 1933. *Beauty and other forms of value.* Macmillan, London.

(4) ALLMAN, G. J. 1880. "On 'Limnocodium victoria', a hydroid medusa of fresh water." *Nature*, 22, p. 178.

(5) ALLPORT, N. L. 1936. "*p*-Aminobenzenesulphonamide." *Quart. Journ. Pharm.* 9, p. 560.

(6) ANDRADE, E. N. DA C. 1938. "Science in the seventeenth century." *Nature*, 142, p. 19.

(7) ANONYMOUS. 1908. Article on Cavendish in *The illustrated Chambers's Encyclopaedia.* Chambers, London.

(8) ARMSTRONG, E. F. 1941. "Henry E. Armstrong." *Nature*, 147, p. 373.

(9) BACON, F. 1605. *The advancement of learning.* Reprinted in Everyman's Library. Dent, London. (For Bacon see also Verulam.)

(10) BAKER, J. R. 1940. "Science in the U.S.S.R." *New Statesman and Nation*, 2nd March, p. 276.

(11) BAKER, J. R. and J. B. S. HALDANE. 1934. *Biology in everyday life.* Allen and Unwin, London.

(12) BARKER, E. 1929. Article on Aristotle in the *British Encyclopaedia*, 14th edition. London.

(13) BARRETT-HAMILTON, G. E. H. 1913. *A history of British mammals.* Gurney and Jackson, London.

(14) BATESON, B. 1928. *William Bateson, naturalist: his essays and addresses, together with a short account of his life.* Cambridge University Press.

(15) BERNAL, J. D. 1939. *The social function of science.* Routledge, London.

(16) BERNAL, J. D. 1941. "Present day science and technology in the U.S.S.R." *Nature*, 148, p. 360.

(17) BROOMHEAD, W. W. (No date.) *Poultry breeding and management.* New Era Publishing Co., London.

(18) BRUNIES, S. 1920. *Der schweizerische Nationalpark.* Schwabe, Basel.

(19) BUCKLEY, H. 1927. *A short history of physics.* Methuen, London.

(20) CAJORI, F. 1899. *A history of physics in its elementary branches.* Macmillan, London.

(21) CARTRIGHT, G. 1792. *A journal of transactions and events, during a residence of nearly sixteen years on the coast of Labrador.* 3 vols. Allin and Ridge, Newark.

(21*a*) CATTELL, R. B. 1934. "Occupational norms of intelligence, and the standardization of an adult intelligence test." *Brit. Journ. Psychol*, 25, p. 1.

(21*b*) CATTELL, R. B. 1937. "Some further relations between intelligence, fertility and socio-economic factors." *Eug. Rev.*, 29, p. 171.

(22) COLLIP, J. B. 1941. "Frederick Grant Banting, discoverer of insulin." *Sci. Monthly*, May, p. 473.

(23) COWDRY, E. V. 1938. *A textbook of histology: functional significance of cells and intercellular substances.* Kimpton, London.

(24) CROOKES, W. See Gregory (55).

(25) CROWTHER, J. A. 1941. "Science and government." *Nature*, 147, p. 415.

(26) CROWTHER, J. G. 1941. *The social relations of science.* Macmillan, London.

(27) CUVIER, LE CHER. 1817. *Le règne animale distribué d'après son organization.* 4 vols. Deterville, Paris.

(28) DALCQ, A. M. 1938. *Form and causality in early development.* Cambridge University Press.

(29) DANIEL, W. B. 1801. *Rural sports.* Bunny and Gold, London.

(30) DARLING, F. F. 1938. *Bird flocks and the breeding cycle: a contribution to the study of avian sociality.* Cambridge University Press.

(31) DARBISHIRE, A. D. 1911. *Breeding and the Mendelian discovery.* Cassell, London.

(32) DARROW, K. 1941. Review in *Nature*, 147, p. 367, of "Science, philosophy and religion; a symposium", New York, 1941, including article by Darrow.

(33) DARWIN, C., assisted by F. DARWIN. 1880. *The power of movement in plants.* Murray, London.

(34) DARWIN, C. 1888. *Insectivorous plants.* Murray, London. (The first edition was published in 1875.)

(35) DARWIN, C. 1913. *The descent of man, and selection in relation to sex*, 2nd edition, reprinted. Murray, London.

(36) DARWIN, F. 1888. *The life and letters of Charles Darwin.* 3 vols. Murray, London.

(37) DARWIN, F. and A. C. SEWARD. 1903. *More letters of Charles Darwin: a record of his work in a series of hitherto unpublished letters.* 2 vols. Murray, London.

(38) DESOUTTER. 1941. Advertisement in *Daily Telegraph and Morning Post*, 11th June, 1941.

(38*a*) DISNEY, A. N., C. F. HILL and W. E. WATSON-BAKER. 1928. *Origin and development of the microscope.* Royal Microscopical Society, London.

(39) DRAPER, J. W., quoted by Andrade (6).

(40) DRIESCH, H. 1929. *Man and the Universe.* Allen and Unwin, London.

(41) EDWARDS, G. 1941. "Sydney Camm, creator of the Hawker Hurricane." *News Chronicle*, 18th February.

(42) EHRLICH, P. 1886. (No title.) *Zeit. wiss. Mikr.*, 3, p. 150.

(43) EINSTEIN, A. and L. INFELD. 1938. *The evolution of physics: the growth of ideas from the early concepts to relativity and quanta.* Cambridge University Press.

(44) ELTON, C. 1930. *Animal ecology and evolution.* Clarendon Press, Oxford.

(45) ELTON, C. 1933. *Exploring the animal world.* Allen and Unwin, London.

(46) FABRE, A. 1921. *The life of Jean Henri Fabre, the entomologist*, 1823–1910. Dodd, Mead, New York.

(47) FINDLAY, A. 1934. *The spirit of chemistry: an introduction to chemistry for students of the liberal arts.* Longmans, Green, London.

(48) FISHER, J. (No date.) *Birds as animals.* Heinemann, London.

(49) FORD, E. B. 1937. "Problems of heredity in the Lepidoptera." *Biol. Rev.*, 12, p. 461.

(50) FORD, E. B. 1938. *The study of heredity.* Butterworth, London.

(51) GELMO, P. 1908. "Über Sulfamide der *p*-Amidobenzolsulfonsäure." *Journ. prakt. Chem.*, 77, p. 369.

(51*a*) GLADSTONE, J. H. 1874. *Michael Faraday.* 3rd edition. Macmillan, London.

(52) GLASSER, O. 1933. *Wilhelm Conrad Röntgen and the early history of the Roentgen rays.* Bale, Sons and Danielsson, London.

(53) GODLEE, R. J. 1917. *Lord Lister.* Macmillan, London.

(54) GRANT, R. 1852. *History of physical astronomy, from the earliest ages to the middle of the nineteenth century.* Baldwin, London.

(55) GREGORY, R. A. 1916. *Discovery, or the spirit and service of science.* Macmillan, London.

(56) GREGORY, R. A. 1941. "Science and the structure of Society." *Nature*, 148, p. 4.

(57) GREGORY, R. (A.). (On behalf of the British Association.) 1941. "The commonwealth of science." *Nature*, 148, p. 393.

(58) HALDANE, J. B. S. 1932. *The inequality of man and other essays.* Chatto and Windus, London.

(59) HALDANE, J. B. S. 1938. *The Marxist philosophy and the sciences.* Allen and Unwin, London.

(60) HARRISSON, T. 1941. "Mass astrology." *New Statesman*, 16th August.

(61) HARRISSON, T. 1941. "Is science special?" *New Statesman*, 18th October, p. 364.

(62) HARTING, J. E. 1898. *The Rabbit.* Longmans, Green, London.

(63) HEATH, T. L. 1897. *The works of Archimedes.* Cambridge University Press.

(64) HENDERSON, G. C., A. J. GREENAWAY, J. F. THORPE and R. ROBINSON. 1932. *The life and work of Professor William Henry Perkin.* Chemical Society, London.

(65) HESSE, R. 1937. *Ecological animal geography.* Chapman and Hall, London.

(66) HILL, A. V. 1933. "International status and obligations of Science." *Nature*, 132, p. 952.

(67) HOBBES, T., quoted by Huxley, T. H. (79).

(68) HOGBEN, L. T. 1920. "Studies on synapsis. I. Oogenesis in the Hymenoptera." *Proc. Roy. Soc. B*, 91, p. 268.

(69) HOGBEN, L. T. 1920. "On certain nuclear phenomena in the oocytes of the gall-fly Neuroterus." *Trans. Linn. Soc. Zool.*, 34, p. 327.

(70) HOGBEN, L. T. 1921. "Studies on synapsis. III. The nuclear organization of the germ cells in Libellula depressa." *Proc. Roy. Soc. B*, 92, p. 60.

(71) HOGBEN, L. (T.) 1938. *Science for the citizen.* Allen and Unwin, London.

(72) HOLMES, S. J. (No date.) *Louis Pasteur.* Chapman and Hall, London.

(73) HOPKINS, F. G. 1935. "Science in modern life." *Nature*, 136, p. 893.

(74) HOWARD, H. E. 1920. *Territory in bird life.* Murray, London.

(75) HOWARD, H. E. 1929. *An introduction to the study of bird behaviour.* Cambridge University Press.

(76) HUMBOLDT, W. VON, quoted by Mill (98).

(76*a*) HUNT, R. 1908. "Article on Cavendish in *Dictionary of National Biography*, Vol. 3, p. 1257. Smith, Elder, London

(77) HUXLEY, T. H. 1854. Review of "Vestiges of the natural history of creation. 10th edition. London, 1853." *Brit. For. Med.-Chir. Rev.* 13, p. 425.

(78) HUXLEY, T. H. 1855. "On certain zoological arguments commonly adduced in favour of the hypóthesis of the progressive development of animal life in time." *Roy. Inst. Proc.*, 2, p. 82.

(79) HUXLEY, T. H. 1877. "On the study of biology." *Nature*, 15, p. 219.

(79*a*) ILTIS, H. 1932. *Life of Mendel.* Allen and Unwin, London.

(80) INFELD, L. 1941. *Quest: the evolution of a scientist.* Gollancz, London.

(81) JAFFE, B. 1934. *Crucibles: the lives and achievements of the great chemists.* Jarrolds, London.

(82) JEANS, J. 1937. *Science and music.* Cambridge University Press.

(83) JONES, R. A. 1941. "The man of science as aristocrat." *Nature*, 147, p. 677.

(83*a*) KOBBÉ, G. 1925. *The complete opera book.* Putnam, London.

(84) KROPOTKIN, PRINCE. Quoted by Marchant (92).

(85) LANKESTER, E. R. 1880. "On a new jelly-fish of the order Trachomedusae, living in fresh water." *Nature*, 22, p. 147.

(86) LANKESTER, E. R. 1880. "The freshwater Medusa." *Nature*, 22, p. 177.

(86*a*) LISTER, J. 1909. Article on "Joseph Jackson Lister" in *Dictionary of National Biography.* Smith, Elder, London.

(87) LITCHFIELD, H. 1915. *Emma Darwin: a century of family letters, 1792–1896.* 2 vols. Murray, London.

(88) LODGE, O. Quoted by Andrade (6).
(89) LYND, R. S. Quoted by Waddington (139).
(90) M——, H. G. 1941. *Book review in Journ. Soc. Pres. Fauna Emp.*, 42, p. 52.
(91) MACLEOD, J. J. R. 1924. "Insulin." *Physiol. Rev.*, 4, p. 21.
(92) MARCHANT, J. 1916. *Alfred Russel Wallace: letters and reminiscences.* Cassell, London.
(93) MASSON, J. I. O. 1940. "The universities and research." *Nature*, 145, p. 855.
(94) McKIE, D. 1935. *Antoine Lavoisier, the father of modern chemistry.* Gollancz, London.
(95) MEES, C. E. K. 1929. Article on "Photography" in the *British Encyclopaedia*, 14th edition.
(96) MIDDLETON, A. D. 1930. "The ecology of the American grey squirrel (*Sciurus carolinensis* Gmelin) in the British Isles." *Proc. Zool. Soc.*, p. 809.
(97) MIDDLETON, A. D. 1931. *The grey squirrel.* Sidgwick and Jackson, London.
(98) MILL, J. S. 1859. *On liberty.* Reprinted in *Utilitarianism, liberty and representative government* in Everyman's Library. Dent, London.
(99) MILL, J. S. 1863. *Utilitarianism.* Reprinted in *Utilitarianism, liberty and representative government* in Everyman's Library. Dent, London.
(100) MILLER, E. C. 1938. *Plant physiology with reference to the green plant.* McGraw Hill, London.
(101) MILLER, H. 1841. *The old red sandstone.* Reprinted in Everyman's Library. Dent, London.
(102) MILLER, H. 1881. *Footprints of the creator.* Nimmo, Edinburgh.
(103) MOORE-BRABAZON, J. T. C. 1941. "The man of science as aristocrat." *Nature*, 147, p. 544.
(104) MORGAN, T. H. 1907. *Experimental zoology.* Macmillan, London.
(105) MORTIMER, R. 1940. "Books in general." *New Statesman and Nation*, 2nd March, p. 277.
(106) MORTIMER, R. 1941. "Books in general." *New Statesman and Nation*, 18th October, p. 363.
(107) PARSONS, T. R. 1930. *The materials of life.* Routledge, London.
(108) PEARSON, K. 1900. *The grammar of science.* Black, London.
(109) PLUTARCH. Quoted by Whymper, E. (144).

(110) POLANYI, M. 1939. *Rights and duties of science.* Manch. School econ. soc. stud., October, p. 175.

(111) POLANYI, M. 1940. *The contempt of freedom: the Russian experiment and after.* Watts, London.

(112) REMSEN, I. and C. FAHLBERG. 1879–80. "On the oxidation of substitution products of aromatic hydrocarbons." *Amer. Chem. Journ.* 1, p. 426.

(113) REYNOLDS, Q. 1941. Quoted in *News Chronicle.* 11th August.

(114) RIMSKY-KORSAKOFF, N. A. Quoted by Kobbé (83*a*).

(115) ROHR, M. VON 1936. *Abbe's apochromats.* Zeiss, Jena.

(116) ROMANES, G. J. 1880. "Physiology of the freshwater Medusa," *Nature*, 22, p. 179.

(117) ROMANES, G. J. 1882. *Animal intelligence.* Kegan Paul, Trench, London.

(118) RUSSELL, B. 1941. *Let the people think: a selection of essays.* Watts, London.

(119) S——, R. A. 1869–70. (Obituary notice of Graham.) *Proc. Roy. Soc.* 18, p. xvii.

(120) SCHULTZ, G. 1890. "Bericht über die Feier der Deutschen Chemischen Gesellschaft zu Ehren August Kekulé's." *Ber. deut. chem. Ges.* 23, p. 1265.

(121) SKENE, M. 1935. *A flower book for the pocket.* Oxford University Press.

(122) SPENCER, H. 1869. *The classification of the sciences, to which are added reasons for dissenting from the philosophy of M. Comte.* Williams and Norgate, London.

(123) STURGES, T. W. 1915. *The poultry manual: a complete guide for the breeder and exhibitor.* Macdonald and Evans, London.

(124) SWIFT, J. 1726. *Travels into several remote nations of the world by Lemuel Gulliver, first a surgeon, and then a captain of several ships.* Reprinted by Penguin Books, Harmondsworth, 1938.

(125) SWINTON, W. E. 1934. *The Dinosaurs, a short history of a great group of extinct reptiles.* Murby, London.

(126) TANSLEY, A. G. 1929. *The new psychology and its relation to life.* 11th impression. Allen and Unwin, London.

(127) TAYLOR, F. S. 1940. *The conquest of bacteria: from* 606 *to* 693. Secker and Warburg, London.

(128) THIMANN, K. V. and J. B. KOEPFLI. 1935. "Identity of the growth-promoting and root-forming substances of plants." *Nature*, 135, p. 101.

(129) THORNDIKE, L. 1923. *A history of experimental science.* Vol. 1. Macmillan, New York.

(130) THORPE, E. 1911. *Essays in historical chemistry.* Macmillan, London.

(131) THORPE, E. 1926. *A dictionary of applied chemistry.* Vol. 6. Longmans, Green, London.

(132) TILDEN, W. Quoted by Gregory (55).

(133) TILDEN, W. A. 1922. *Chemical discovery and invention in the twentieth century.* 4th edition. Routledge, London.

(134) TRÉFOUËL, J. and J., F. NITTI and D. BOVET. 1935. "Activité du *p*-aminophénylsulfamide sur les infections streptococciques experimentales de la souris et du lapin." *Compt. rend. Soc. biol.* 120, p. 756.

(135) TRUEMAN, A. E. 1938. *The scenery of England and Wales.* Gollancz, London.

(136) VALLERY-RADOT, R. 1900. *La vie de Pasteur.* Hachette, Paris.

(137) VERULAM, FRANCIS (LORD). 1658. *Sylva Sylvarum: or, A Natural History.* 7th edition, edited by W. Rawley. Lee, London.

(138) VERULAM, FRANCIS, LORD. (No date, probably 1660.) *New Atlantis. A work unfinished.* Edited by W. Rawley. Lee, London.

(139) WADDINGTON, C. H. 1941. *The scientific attitude.* Harmondsworth (Pelican).

(140) WALLACE, A. R. 1894. *The Malay archipelago.* Macmillan, London.

(141) WATSON-BAKER, W. E. 1941. *Personal communication.*

(141*a*) WELLS, H. G. 1941. "The man of science as aristocrat." *Nature,* 147, p. 465.

(142) WENT, F. W. and K. V. THIMANN. 1937. *Phytohormones.* Macmillan, New York.

(143) WEST, E. S. 1941. "Beethoven and the future." *New Statesman and Nation,* 5th April, p. 363.

(144) WHYMPER, E. (No date.) *Scrambles amongst the Alps in the years 1860–69.*" 5th edition. Nelson, London.

(145) ZAREK, O. 1941. *German odyssey.* Cape, London.

(146) ZOETHOUT, W. D. and W. W. TUTTLE. 1940. *A textbook of Physiology.* 7th edition. Kimpton, London.

Index

OVERLEAF

particulars of publications
of similar interest
issued by

GEORGE ALLEN & UNWIN LTD
LONDON: 40 MUSEUM STREET, W.C.1
CAPE TOWN: 58–60 LONG STREET
SYDNEY, N.S.W.: 65 YORK STREET
TORONTO: 91 WELLINGTON STREET WEST
BOMBAY: 15 GRAHAM ROAD, BALLARD ESTATE
WELLINGTON, N.Z.: 8 KINGS CRESCENT, LOWER HUTT

New Paths in Genetics

by J. B. S. Haldane, F.R.S.

La. Cr. 8vo *With text diagrams* *7s. 6d. net*

Professor Haldane deals largely with the relations of genetics to other branches of biology, such as embryology and biochemistry, and to medicine. Based on lectures delivered at a Dutch University, it is largely an account of work done under his direction, or by himself. After an introduction surveying the whole field of genetics, two chapters deal with the question of what genes actually do. It is shown that the answer to this question throws a good deal of light on normal metabolism and development. The rest of the book is concerned with human heredity, especially the heredity of abnormalities and diseases. Special attention is paid to mental defect and inbreeding. In the last chapter methods are described by which human chromosomes have been partially mapped. It turns out that we actually know more about some aspects of the genetics of man than of the mouse or rabbit. The book will be a revelation to those who believe that genetics is mainly concerned with the breeding of small flies in bottles, and should be read not only by geneticists, but by biologists and medical practitioners and students.

Race, Reason and Rubbish

by Gunnar Dahlberg

Cr. 8vo *Translated by* Lancelot Hogben, F.R.S. *8s. 6d. net*

In this book the outstanding Swedish geneticist Gunnar Dahlberg issues a challenging critique of the Nazi race doctrine within the framework of a lucid popular exposition of modern work on inheritance. It now appears in English for the first time, translated from the Swedish by our most successful expositor of natural science in relation to the responsibilities of citizenship. This translation by Lancelot Hogben should appeal to all thinking men and women who wish to have a deeper understanding of the fallacies inherent in current Nazi propaganda.

The World and the Atom

by C. Moller *and* Ebbe Rasmussen

Foreword by Professor Niels Bohr

Translated by G. C. Wheeler *and* Bernard Miall

Demy 8vo *Illustrated* *10s. 6d. net*

"This little book on atomic physics for the general reader comes like a breath from a finer world. It is written by two colleagues of Niels Bohr and does indeed reflect the finest spirit of the period between the wars."—*Manchester Guardian*

LONDON: GEORGE ALLEN & UNWIN LTD